Global Network for Isotopes in Precipitation
GNIP

Global Network for Isotopes in Precipitation

To Joël Gat and Hans Oeschger
The water cycle

in particular has the potential for focusing the attention of scientists, politicians, policy makers and the public at large, because it embraces some of the most acute problems facing many societies, and it is the main link between the physical climate system and biogeochemical cycles.

The International Geosphere Biosphere Programme together with the World Climate Research Programme view the understanding of the water cycle as essential for reaching the scientific goals of their programmes. Isotopes in the water molecule are an indispensable tool for understanding both past changes and the present behaviour of global circulation. Thus we strongly support the recommendations of the IAEA/WMO/PAGES workshop, and endorse the proposed initiative to reorganize and enhance GNIP to better meet the needs of climate and global change research.

Chris Rapley
Executive Director, IGBP

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Director, WCRP
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Whilst the Global Network for Isotopes in Precipitation is expected to fulfill an increasing range of new tasks, eg, to link present climatic conditions to paleo-climatic archives, in reality there has been a progressive closure of long-term stations.

Operational stations of GNIP 1994-1995

The USA share with the former USSR and Africa the distinction of having one of the largest gaps in the GNIP network.
This GNIP booklet is in response of ongoing international activities to stop the decline and to reorganize the current isotope network. At the Rüttilhubelbad workshop the main recommendation formulated by the participating scientists and representatives of the organizing agencies and programmes emphasized that:

"The structure of GNIP should be strengthened. This includes the build-up of stations located close to major natural archives which provide important information on paleo-precipitation, and stations which represent climatically sensitive areas as indicated by global circulation and biome models."

To achieve and not merely formulate this goal, active support from all parties, the scientific community, the global change programmes, and the funding agencies is necessary.

Though isotope data are indispensable for the specialist, they have still the touch of a magic tool for a broad scientific community. We think the best way to promote their use is to show their applicability.

The GNIP booklet therefore transmits the necessary scientific background rather by images than by scientific reasoning. Short text passages highlight scientific facts. Potential GNIP contributions to international global change programmes as well as to the individual researcher seeking a deeper understanding of the water cycle are outlined. The booklet does not replace scientific textbooks. It aims at stimulating interest in further reading.

Background literature and review articles from the Rüttilhubelbad workshop are listed at the end.
TRACING ISOTOPIC COMPOSITION OF PAST AND PRESENT PRECIPITATION: OPPORTUNITIES FOR CLIMATE AND WATER STUDIES

Workshop in Rüthihubelbad, Switzerland, 23-25 January 1995

This workshop was jointly organized by WMO, IAEA, IAHS, and PAGES, a core project of IGBP. Experts and representatives of national and international organizations shared their interest in isotope, climate and water studies and discussed future directions of GNP.

The efforts of IAEA in promoting isotope methods in studies related to the hydrological cycle, including continuous operation of GNP over the past three decades were acknowledged. GNP has gained international recognition as one of the key elements in all global change studies concerned with the evolution of the water cycle and climate. The network is now expected to serve additional purposes, namely as a benchmark for the interpretation of paleo-records, as a validation tool for global circulation models, and for establishing large scale regional and continental scale water balances.

The recommendations of the working groups addressed, among others the following issues:

- There should be close liaison with WMO stations which measure other atmospheric parameters. Co-operation with programmes such as Global Atmospheric Watch and Global Climate Observing System is recommended.
- Isotope monitoring of river outflow from major continental basins should be initiated. This could be realized in co-operation with the UNEP-WHO Global Environmental Monitoring System-Water.
- National Science Foundations and funding agencies should be approached to provide funds for strengthening GNP and national networks, which could in turn contribute to the global data base.
OPERATIONAL ASPECTS OF THE GLOBAL NETWORK FOR ISOTOPES IN PRECIPITATION
Consultants meeting, Vienna, Austria
7-10 November 1995

The Rüttihubelbad meeting requested that specific steps be taken towards strengthening the operation of the network with broader participation and support from national and international bodies dealing with water and climate. The Vienna meeting formulated a Memorandum of Understanding on joint operation of the GNIP. It proposed a Scientific Steering Committee to be established in 1996 which will be responsible for ensuring that the network is properly designed, operated and maintained.

The organizations and programmes envisaged as being represented on the SSC include the specialized UN agencies IAEA, WMO, UNEP, WHO; the global change research programmes IGBP (most directly through PAGES) and WCRP; the scientific union IAHS.

The participating organizations would be responsible for the following:

IAEA
Analytical aspects, quality assurance and control, laboratory intercalibrations, data archiving and management.

WMO
Precipitation sampling, station maintainance, provision of samples to laboratories, liaison with national agencies.

WMO/WHO/UNEP
River sampling, station maintainance.

IGBP-PAGES/WCRP
Ensuring that the network is meeting the needs of global research efforts dealing with the water cycle and climate.

The SSC should conduct reviews at three to five year intervals to re-assess the network.
Ice core data from Antarctica proved for the first time the close relationship between greenhouse gases and atmospheric temperature on timescales covering a full glacial cycle. These findings also supported the 1990 assessment from the Intergovernmental Panel on Climate Change (IPCC) on global warming due to anthropogenic greenhouse gas emissions. The assessment was reaffirmed in 1992 and 1995:

"We are certain that emissions resulting from human activities are substantially increasing the atmospheric concentrations of the greenhouse gases: carbon dioxide, methane, CFCs and nitrous oxide. These increases will enhance the greenhouse effect, resulting on average in an additional warming of the Earth's surface. The main greenhouse gas, water vapor, will increase in response to global warming and further enhance it."

IPCC further stated, that a steady rise would be unlikely. Almost every year of the last decade has produced a new record in global warming. Only the cooling ash clouds from Pinatubo interrupted this trend. 1995 was on top of the charts again.

Is this already a sign of human interference with the climate system?

The greenhouse gas concentrations in the atmosphere have already reached levels above those recorded over the last 250,000 years. Due to the inertia of the oceans, atmospheric temperature lags but are we still within the range of natural variability?
A gradual global warming may be tolerable, but the main impacts arising from anticipated global warming will be caused by changes in the water cycle.

A major impediment predicting these impacts is the short period of time for which instrumental records are available. An extension of the instrumental data by the addition of proxy records is in principle possible.

The isotopes of the water molecule offer such an opportunity. They label individual components of the hydrological cycle and describe the past by archiving continuously the climatic and hydrological conditions prevailing at the time. For quantitative interpretations they need to be calibrated. This implies an adequately designed present day network.
The physical climate system and the biogeochemical cycles

Global change has always been the context for human life. Now we are accelerating its pace by interfering with the physical climate system and the geochemical cycles. Unable to foresee all the consequences of our activities, we fear we may be faced very soon with serious natural hazards. Hopefully we are beginning to realize the human dimensions of self-induced global change. The interplay between the physical climate system and the biogeochemical cycles is complex and highly non-linear. It takes place on numerous scales in time and space. The physical climate system incorporates the atmospheric and oceanic processes that govern the distribution of temperature and precipitation on the surface of the Earth. This includes motions driven by differential solar heating and the changing albedo. The biogeochemical cycles are characterized by the flow of key substances such as carbon, sulfur, nitrogen or phosphorus through the global environment. They influence living matter and are controlled by it.

Water is the conveyor belt, which keeps these processes in motion. Through drought or excess it defines the limits of our existence. It inextricably ties the Human Dimensions of Global Change to the Physical Climate System and the Biogeochemical Cycles.

The ECHAM 4 model of the Hamburg Max Planck Institute for Meteorology reproduces quite nicely the most recent data on global fluxes of water.
The global water cycle

Our current fixation with anthropogenic greenhouse gas emissions can distract us from the reality, that water vapour is the most important greenhouse gas. It plays a major role in regulating the global climate system. Any change in the radiative balance of the atmosphere will consequently lead to changes in evaporation and precipitation.

Advanced global circulation models provide not only a general understanding of the hydrological cycle today, they also reproduce quantitatively the most recent estimates of global water fluxes. But they emphasize average conditions. Society will be most vulnerable to extreme events.

To what extent can isotope methods help to reduce the uncertainties surrounding our understanding of their occurrence?
The radioactive isotope tritium (\(^3\)H) and the stable isotopes deuterium (\(^2\)H) and oxygen-18 (\(^18\)O) are rare components of the water molecule H\(_2\)O. They offer a broad range of possibilities for studying processes within the water cycle. Tritium was released to the atmosphere during the test phase for hydrogen bombs. The very low natural levels were overwhelmed by concentrations several orders of magnitude higher. Since then, tritium levels have been progressively decreasing due to washout processes and the admixture of moisture from the oceans. Due to the long residence time of ocean water as compared to the half life of tritium containing deuterium-18 (\(^18\)O) is heavier \(^18\)H\(^2\)H\(^18\)O molecules forming precipitations in heavy isotopes water. Condensation drops from a cloud to the oceans. Tritium, deuterium and oxygen-18, label the global water cycle.

The isotope of the water molecule, tritium, deuterium and oxygen-18, label the global water cycle.

(up to 2000 years and 12.4 years respectively) the oceans act as a sink for tritium. Tritium in precipitation has been monitored since the beginning of the bomb tests in late 1952. These data enabled the establishment of timescales for the transport of water through different compartments of the hydrological cycle. For example, groundwater which does not contain tritium must have infiltrated as rain before 1952 because the natural concentrations have already decayed below the detection limit. If one measures 1000 tritium units (TU) in glacier ice, this layer must originate from snowfalls in 1963. It was the time when tritium injections to the atmosphere reached a maximum.

The stable isotopes label in a different way: since a water molecule that the illustrated mil values relate to on a broad scale II Heavy rains are in light rains, summer less depleted than winter. Precipitation in isotopically light latitudes, groundv from infiltration at lighter than those fo
Low natural levels of concentrations of tritium are already decayed. Water levels have been raised due to washing the admixture of oceans. Due to the half-life of tritium, the natural content of tritium in the water is enriched, and the cloud moisture is subsequently depleted as the rain out continues.

The isotopic fractionation during phase transitions (vapour-liquid-solid) is temperature dependent. A water sample is thus labelled depending on the environmental conditions it has experienced. It is therefore obvious that the illustrated examples (the per mil values relate to oxygen-18) vary on a broad scale in space and time. Heavy rains are more depleted than light rains; summer precipitation is less depleted than winter precipitation. Precipitation in polar regions is isotopically lighter than in low latitudes, groundwaters originating from infiltration at high altitudes are lighter than those formed in lowlands.

Surface waters preferentially loose the lighter water molecules due to evaporation. They are often enriched in heavy isotopes as compared to the isotopic composition of rainwater from which they were formed.

A global network of isotopic input data is necessary to decipher this ongoing tracer experiment in the laboratory of nature.
The first precise determinations of stable isotope ratios in meteoric waters performed in the early fifties revealed a large variability in the isotopic composition of precipitation, both in time and space. The need for worldwide tritium measurements was brought about by the nuclear weapon tests, which vastly exceeded the natural levels.

In 1961, the International Atomic Energy Agency (IAEA) in cooperation with the World Meteorological Organization (WMO) started a world-wide survey of the isotopic composition of monthly precipitation. During the initial phases, tritium monitoring was the central activity. The network has provided a detailed and complete picture of the increase of tritium levels in precipitation and its decrease to nearly natural levels at the present day.

The programme was also launched with the primary objective of collecting systematic data on the isotope content of precipitation on a global scale and, consequently, to provide basic isotopic data for the use of environmental isotopes on hydrological investigations. It become apparent soon that the collected data were also useful in other water-related fields such as oceanography, hydro-meteorology and climatology.

Prior to the high precision measurements the sample has to be properly taken and shipped. To avoid contamination or evaporation causing misleading results, the IAEA lab provides guidance on the proper handling procedure.

The stable isotope ratios deuterium/hydrogen and $^{18}\text{O}/^{16}\text{O}$ of water are measured in a mass spectrometer and expressed by convention as parts per thousand deviation from the Vienna Standard Mean Ocean Water (V-SMOW has isotope ratios $^{2}$H/$^{1}$H=156*10$^{-6}$ and $^{18}$O/$^{16}$O=2005*10$^{-6}$). The delta notation $\delta^{2}$D or $\delta^{18}$O is used to report stable isotope variations in water samples. The tritium/hydrogen ratio is much smaller. It is commonly expressed in tritium units (1TU=1*10$^{-10}$). Tritium therefore has to be measured by its radioactive decay.

To guarantee quality control and to support member states, the IAEA set up an isotope laboratory in Vienna. Intercomparison tests and expert meetings are organized regularly to distribute information on advanced technology and applications.
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Tracing the transient behaviour of bomb tritium has provided a unique opportunity to study short term processes in the hydrosphere. In particular the knowledge of the input concentration allows us to calculate model-based residence times of groundwater. The inset figure shows the model based tritium output concentrations during the last decade for different residence times (exponential age distribution northern hemisphere).

The close and consistent proportionality between deuterium and oxygen-18 in meteoric waters, defined by the best fit line ($\delta D=8\delta^{18}O+10$) and commonly known as Global Meteoric Water Line, GMWL, is the base of many hydrological and climatological applications. Distinct deviations from its slope of 8 are caused by evaporation, especially in low latitudes and semi-arid regions.

Exchange processes within an aquifer, which may modify the stable isotope ratio due to the specific geological setting, offer additional tracer opportunities. It is therefore recommended to measure, whenever possible, both isotopes, deuterium and oxygen-18.
Since 1953 over 100,000 isotope measurements have been performed within the GNIP programme. Two thirds stem from cooperating laboratories and national networks, the rest has been measured in the IAEA laboratory. In total the data originate from 315 different stations. Full years often could not be covered, which makes statistical treatment difficult. The data were critically revised several times, and obviously anomalous results rejected.

The network started with 100 meteorological stations collecting data from 60 different countries. The maximum of 220 stations was reached in 1962/63.

After the nuclear weapon test moratorium and the decline of tritium in the atmosphere, the number of network stations started to decline too. For many contributing countries and organizations, GNIP seemed to have fulfilled its intended function. Since sampling is done in most cases on a voluntary basis, this may have accelerated the trend. Empty sampling bottles were returned to the IAEA laboratories, important long-term key stations were closed and the distribution of data became more and more patchy.

Valentia Island, off the west coast of Ireland, experiences the brunt of the North Atlantic Oscillation and its impacts on European weather. It is one of the stations with the longest isotope records.
we been performed operating laboratories in the IAEA laboratories. Full years often difficult. The data rejection results rejected.

work started with 100 stations collecting data in 1975. The 20 stations were in 63 countries. The weapon test moratorium of tritium in the number of netted to decline too. Using countries and NIP seemed to have led function. Since in most cases on a 15 may have accelerated sampling related to the IAEA laboratories long-term key and the distribution more and more

But the signatures of isotopes in precipitation are not static. They respond to both, synoptic climatology and global climate change. Attracted by this issue, a new community, interested in palaeoclimatic and atmospheric circulation modeling, started to use the GNIP data. In recognition of the many advantages of isotope data, new national networks have been established and contributed to GNIP. Switzerland for example has already added 118 rivers and shallow groundwater to their network.

VALENTIA (OBSERVATORY), IRELAND

The isotope and meteorological data are published in data books and are also available on floppy discs. Direct access to the GNIP data base is possible via Internet:

http://www.iaea.org/programmes/11/gnip/gnipmain.htm

At the Rüttlibelbad and Vienna expert meetings, first steps towards a reorganization of the network were made. It was recognized that national networks will play a significant role in the future GNIP. Specialists from Russia and the US expressed willingness to co-operate in enhancing GNIP activities in their respective countries. A special meeting on an African network is planned. To re-open and/or to secure the operation of existing long-term stations, together with the definition of index stations, will be high on the agenda of the planned steering committee.
Nearly all the water molecules forming precipitation originate from the ocean and return after their individual and often comparable travel through the water cycle to the ocean again. The mean residence time ranges from days to month in the atmosphere, to years, centuries and millennia on the continents and in the oceans, to several hundred thousand years in Antarctica. The history of a molecule is strongly influenced by the differences in ocean-continent distribution. It follows that the isotopic composition of water covers a broad spectrum in space and time.

Phase changes of water (solid-liquid-vapor) lead to isotopic fractionation, because the saturation vapor pressures of $^1$H$^2$H$^18$O and $^1$H$^2$H$^2$H$^16$O are slightly lower than that of $^1$H$^2$H$^18$O. A Raleigh model considers the isotopic fractionation occurring in an isolated air parcel. Condensation is assumed to take place under equilibrium conditions with the surrounding water vapor followed by immediate or progressive rain-out.

The major sources of water vapor are the tropical oceans. Poleward transport of this water results in gradual rainout and thus in a depletion of the remaining moisture in deuterium and oxygen-18. The latitudinal distribution of long-term annual means of oxygen-18 from the GNIP data base illustrate this behaviour.
The observed isotope distribution in space and time can be related to a number of environmental parameters which characterize not only the source region but also a given sampling site. Seasonality, amount of precipitation, altitude dependence, continentality, the role of local temperature, together with the source specific fractionation between oxygen-18 and deuterium: all these effects can contribute to the isotope content of a sample of precipitation.

The attraction to use stable isotopes in paleoclimate studies has mainly derived from their relation to atmospheric temperature. Using examples from the GNIP data base we want to show that the focus on atmospheric temperature alone may not always lead to the best results when using isotopes as paleo-indicators of climate.

The seasonal variation of oxygen-18 and temperature in Hong Kong (22°N, 114°E), controlled by monsoon climate, shows an anticorrelation. The dominant isotopic depletion by heavy summer rains suppresses the temperature effect. The mid latitude station Meiringen (46°N, 08°E) shows the opposite behaviour with less negative values in summer time reflecting the increased temperature. Depending on the latitude, rainfall intensity or temperature may dominate the seasonal distribution of isotopes in precipitation.
A closer look at different latitudinal zones confirms this.

- In mid and high latitudes, the isotopes in monthly precipitation are correlated with temperature. Seasonally changing temperatures lead to variations in the total precipitable water in the atmosphere, due to the varying degrees of rain-out from airmasses as they are transported polewards.
- Low latitudes show a different response. Isotopic content is modulated by the seasonal variations in the volume of precipitation instead. During the rainy season, precipitation is isotopically depleted.

The apparent correlation between the amount of monthly precipitation and its isotopic composition illustrates an important aspect of the GNIP data for tropical marine stations. The long-term monthly and annual mean values for oxygen-18 correlate well with the average monthly amount of precipitation, whereas the correlation with temperature is virtually nonexistent.

Long term monthly (shaded) and annual (dots) mean values for oxygen-18 in precipitation compared with temperature and precipitation (yearly means are divided by 12) for tropical island stations. Rain-out masks the temperature effect.

Individual and long-term monthly means (shaded area and dots respectively) from an alpine mid latitude station. Isotopes in precipitation are not only correlated with temperature but also with the long-term variations in the monthly amount of precipitation.

From the G that the expression both stable isotope is gradually enhance moisture moves into the European continent. It is about 2.5% in Va Moscow. This so-called effect is reduced in to the recycling of a nature by evapo-trans
From the GNIP data we see that the expression of seasonality in both stable isotopes and temperature is gradually enhanced as the oceanic moisture moves inland across the European continent. The seasonal variation in oxygen-18 increases from about 2.5% in Valencia to 10% in Moscow. This so-called continental effect is reduced in summer time due to the recycling of atmospheric moisture by evapo-transpiration.

For some tropical continental stations, the amount of local rain-out seems to be not the only control for isotopic composition. Changes in the moisture of the source region may contribute too. During the period of maximum of precipitation in the Amazon region (Manaus), the ITCZ pushes isotopically depleted moisture inland. This negative isotope signal is visible also 2000km further west in Izobamba.
Continentality

When clouds move inland from the coast, they become isotopically depleted progressively, as a result of their loss of moisture. The isotopic signatures also reflect the topography of the continent. Mountain chains deplete the clouds too, because of orographically forced rain-out. The degree of continentality, as defined by the isotopes, is a function of the effect of the steep temperature gradient between the ocean and the interior especially in winter. This leads to progressive isotopic depletion as precipitable water is lost with the passage of air inland. This process prevails for as long as the ocean is the dominant moisture source and re-evaporated moisture does not play a major role.

The transect across the South American Continent at low latitudes differs remarkably from the European example. Variations in the seasonal isotopic composition are less and the gradient from the coast inland is small, except in the Andean region, where the altitude effect dominates. One reason for the difference is the reduced temperature gradient in the lower latitudes, another is the greater importance of recycled moisture over the Amazon and Orinoco basins.
A transect of yearly average isotopic values in precipitation, from the Weathership in the North Atlantic over Valentia to Moscow, shows oxygen-18 decreasing inland. The gradient varies seasonally and, for the reasons given above, it is more pronounced in winter than in summer.

A modelled isotope transect through Northern California. The calculated isotopic depletion cannot be compared directly with measured values, since the model values shown are for precipitation and the observational data represent springs, wells, and lakes. Data on stable isotopes in precipitation are not available, nevertheless the model gives credible results.
Altitude effect

When air masses are orographically uplifted they cool and precipitate preferentially the heavier isotopes. Depending on the precipitation history, the topographic situation, the degree of cooling and the precipitable moisture left, the altitude effect on oxygen-18 in mid latitudes generally ranges between 0.15 and 0.30 %o for each 100 m of altitude gained. In applied isotope hydrology, this effect is used to estimate the altitude of groundwater recharge areas.

The example from the Bernese Alps in Switzerland is a composite of data from monthly precipitation and a well dated ice core. The long-term average of oxygen-18 decreases from -10%o at 500 m to -17%o at 4000 m.

The influence of both latitude and prevailing seasonal moisture circulation is illustrated in the example from South America. In the equatorial region, the position of the ITCZ controls, to a large extent the amount of rainfall. Up to 3000 m, the average decrease in oxygen-18 is 0.2%o per 100 m; above this altitude it falls more rapidly (0.5%o per 100 m). The possible explanation may be seen in the forced rainout of already isotopically depleted moisture onto the steep ridges of the high Andes. The profile at 33°S reveals the opposite trend with a steeper oxygen-18 altitude gradient in the lowlands (0.6%o/100 m). The reason for this behaviour is still not well understood, but it is clear, that the great latitudinal extent of the Andes form a barrier between the Atlantic and the Pacific moisture regimes. This may play a major role in the stable isotope distribution on the South American Sub-continent.

Due to the lack of systematic isotopes in precipitation measurements, the example is based on composite data from precipitation, rivers, and springs taken at different time intervals. Latitudinal isotope transects across the Andes are needed to further our understanding of the relationship between precipitation and dominant moisture sources. Recently, the national Chilean network for isotopes in precipitation became operational. Most of the stations are situated along the Pacific coast and may form starting points for transects across the Andes.
Physically uplifted they formed the heavier isoplation history, the effect on oxygen-18 for each 100 m of is used to estimate the Bernese Alps. A composite of data from and a well dated ice core at 500 m to -17% at 3000 m. The possible explanation in the forced rain shadow due to the high Andes is the opposite oxygen-18/altitude gradient (0.6%/100 m). The data is still not well clear. The great Andes form a barrier and the Pacific water may play a major role in the stable isotopes distribution on the South American Sub-continent.

Prevailing seasonal moisture distribution controls the stable isotopes in precipitation on the South American Sub-continent.
Deuterium excess

The close relationship between deuterium and oxygen-18 in freshwaters, including precipitation, gives rise to the GMWL, the best fit line ($d = 8\delta^{18}O + 10$) of all data points. The concept of the deuterium excess ($d$) is defined as $d = 8\delta^{18}O$. This relationship is also well understood and can be reproduced by models based on the Raleigh approach. In addition to the phase changes under equilibrium conditions, a kinetic effect results from a different diffusivity for the isotopically different water molecules in air. The higher diffusivity for $^2H^2H^16O$ as related to $^1H^2H^18O$ results in an additional separation, a higher deuterium excess. Humidity relative to saturation at sea surface temperature and wind speed are the major controlling factors. Within-cloud processes do not modify significantly the excess as long as only the formation of precipitation is considered. The result is a clear seasonal response as the hemispheric GNIP data demonstrate.

The deuterium excess can be used to identify vapour source regions. Winter precipitation originating from the Mediterranean Sea is characterized by distinctly higher excess values, reflecting the specific source conditions during water vapour formation.

Increased deuterium excess in precipitation can also arise from significant addition of re-evaporated moisture from continental basins to the water vapour travelling inland. If moisture from precipitation with an average excess of 10‰ is re-evaporated, the lighter $^2H^2H^16O$ molecule may again contribute preferentially to the isotopic composition of the water vapour and this, in turn, leads to an enhanced deuterium excess in precipitation. Examples of deuterium enriched precipitation derived in this way are known from the Amazon Basin, the Great Lakes Region in North America, or from our Mongolian glacier data.

Stable isotope variability in past climate records we know North Atlantic Oscillation (NAO), which is related to change in SST and atmospheric moisture. The oscillating pressure patterns around Iceland and the Azores steer the system's zonal and meridional winds, which, in turn, influence European precipitation patterns.

The GNIP stations Gröningen in the Netherlands have measured both oxygen time series in deuterium of expanding the
Stable isotope records from Greenland ice cores have revealed great variability in past climates, also on decadal time scales. From European climate records we know, that a major source of interannual variability is the North Atlantic Oscillation (NAO), which is related to changes in SST and atmospheric moisture. The oscillating pressure patterns around Iceland and the Azores steer the system of zonal and meridional winds, which, in turn, influence European precipitation patterns.

The GNIP station Groningen in the Netherlands has measured both oxygen-18 and deuterium for three decades; the resulting time series in deuterium excess may offer a link to the NAO with the possibility of expanding this interannual climate index back in time.
The stable isotope thermometer reads differently in different parts of the world.

The link between long-term changes in the isotopic composition of precipitation and surface air temperature at a given location is probably the most important relationship as far as palaeo-climatic applications are concerned. Very soon after GNIP became operational, a semi-empirical temperature/stable isotope relationship was established for coastal stations in the mid and high northern latitudes. The slope of 0.69‰ per °C has been used in numerous climate studies to reconstruct past temperatures.

From what we have seen, this relation may vary over a broad range since local temperature is not always the best measure for the isotopic composition of precipitation at a given site.

In a temperature dominated regime, three different isotope/temperature relationships can be established from the GNIP database: first, the spatially coherent relation between long-term annual averages of stable isotopes and temperature, secondly more local temporal relationship between the two and finally, shorter term the temporal linkage between seasonal changes in stable isotopes and temperature either on a local or more regional scale.
Composite trend curves of oxygen-18 and atmospheric temperature [expressed as deviations from the long-term mean after removing the seasonal trend] from selected European GNIP stations. The close correlation indicates that changes in precipitation patterns or seasonality are of little significance.

Where data show a lack of correlation, or a strong variation in the δ¹⁸O/ΔT gradient, this does not invalidate the isotope approach. It may be that the thermometer has measured precipitation, volume, source or continentality instead.

The data gathered up to now, have revealed a broad spectrum of possibilities for reconstructing hydro-climatic parameters, but we still have to improve our understanding of the physical processes, controlling isotope behaviour in the water cycle. In particular, more information is required from the major source regions of water vapour.

A prerequisite for this is a significant increase in the number of long-term baseline stations and process-oriented case studies, designed to deliver the necessary scientific data base.

Modelling the present day behaviour of stable isotopes in precipitation also reveals the basis for reconstructing past isotope distributions in order to assist in the interpretation of palaeodata. Global Circulation Models generally reproduce well the main characteristics of isotopes on a global scale. Differences show up on regional and local scales, for instance in the tropics, where convective processes are involved. Palaeo-data derived from empirical reconstructions at specific sites provide part of the ground truth for model testing. In this regard isotope data have proved to be of quite outstanding importance.

<table>
<thead>
<tr>
<th>STATION</th>
<th>Long-term δ¹⁸O/ΔT (%/°C)</th>
<th>r²</th>
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<tbody>
<tr>
<td>Hong Kong</td>
<td>0.25±0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>22.32°N, 114.10°E</td>
<td>65 m.a.s.l.</td>
<td></td>
</tr>
<tr>
<td>Ottawa</td>
<td>0.49±0.08</td>
<td>0.14</td>
</tr>
<tr>
<td>45.32°N, 75.60°W</td>
<td>114 m.a.s.l.</td>
<td></td>
</tr>
<tr>
<td>Argentine Island</td>
<td>0.59±0.04</td>
<td>0.45</td>
</tr>
<tr>
<td>65.25°S, 64.20°W</td>
<td>0 m.a.s.l.</td>
<td></td>
</tr>
<tr>
<td>Meiringen</td>
<td>1.10±0.10</td>
<td>0.35</td>
</tr>
<tr>
<td>46.73°N, 8.20°E</td>
<td>632 m.a.s.l.</td>
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The complexities of climate and global change are beyond the scope of single researchers. Scientists have begun to cooperate in a matrix of global programmes under the umbrella of the World Climate Programme and the Global Change Research Programmes.

It is within the mar to apply isotope technology, water-related environmental programmes on V Development. The programme is assessment, management of water resource based methodology and regions suffering water are given priorities are aimed at the the end user of resources. This includes assistance to
The issues related to global environmental change are becoming a cornerstone of many international organizations including both Scientific Unions and the UN system. The IAEA supports research in order to develop isotope techniques and to extend their applicability in hydrology and environmental studies. To this end, the Agency in co-operation with WMO, is conducting a world-wide survey of Isotopes in Precipitation.

Sueo Machi, Deputy Director General, IAEA

It is within the mandate of the IAEA to apply isotope techniques in hydrology, water resources and related environmental fields through its programme on Water Resources Development. The programme is focused on the assessment, management and protection of water resources using isotope-based methodologies. Arid and semi-arid regions suffering from scarcity of water are given priority. The activities are aimed at the direct benefit of the end user of water resources. This includes assistance to developing countries in implementing field investigations, capacity building in isotope hydrology, and transfer of related know-how and technology.

Short-term hydroclimatic evolution will become one of the most important tasks for the scientists of the next century. The highly populated regions influenced by monsoonal oscillations are especially vulnerable to the variability of floods and droughts.

To meet this challenge, the Agency has designed co-ordinated research programmes to improve our knowledge. Scientific conferences and a broad spectrum of publications should help to further promote the application of the integrated use of isotopes in hydrological sciences.

The human dimension of global change: Floods of words cannot replace a drop of water.
Mongolia is perhaps the country with the strongest continentality in the world. Two-thirds of the country, even parts of the widespread desert are sealed by permafrost which hinders penetration to deeper groundwater layers. Average precipitation does not exceed 150 mm a year. The nomadic Mongolian society lives on cattle breeding and thus is depending on the availability of water.

Through an IAEA supported water development programme, isotope methods have been applied to estimate recharge conditions and residence times for groundwater conservation. In this part of the world no time series of input data exist to which the isotope concentrations of the groundwater investigated could be related. The deepfreeze of a cold Mongolian glacier stored the necessary data. A shallow ice core revealed a 20 year history of isotopes in precipitation. The generally higher tritium concentrations as compared to the reference station, Vienna, may be explained by the dominant influence of moisture re-evaporated from parts of the Asian continent, which obviously still release considerable amounts of tritium from nuclear weapon tests. This finding is supported by the less depleted stable isotope values in summer precipitation at the glacier. The respective data points lie above the GMWL, indicating a higher deuterium excess. This, in turn, also points to re-evaporated moisture, most probably from Siberia.

From the tritium in the glacier, the residence time of the groundwater was reconstructed. Finally, the infiltration conditions for Mongolian groundwater could be characterized by comparing its stable isotope composition with the local meteoric water line and the evaporation line as derived from shallow lake water.
Co-ordinated research programmes: Continental isotopic indicators of paleoclimate

During the past three decades, a great variety of isotope methods has been developed and tested with the aim of reconstructing past climatic and environmental changes over the continents. The radioactive isotopes serve as dating tools, the stable isotopes as climate indicators. Together with conservative chemical or the noble gas tracers, they are also preserved in ground-water recharged continuously or intermittently between late Pleistocene and Holocene times. Noble gas contents reflect average ground temperatures for the time the water entered the confined aquifer. They can be related to present day temperature conditions and to stable isotopes in precipitation.

Recharge temperatures in mid and low latitudes during the late glacial as derived from radiocarbon, noble gases, and stable isotopes have initiated a re-consideration of global temperature distribution for that time.
The International Association of Hydrological Sciences represents the scientific hydrological community worldwide. It is composed of nine commissions and committees. The International Committee on Tracers (ITC) links the community.

Though the usefulness of tracers in research is generally recognized, they do not play a significant role in the analysis of extreme events or in component separation. One reason may be that results from classical hydrograph separation often differ from those obtained by tracer methods, which allow additional physical distinctions to be made between different water components.

The convincing demonstration of the value of stable isotopes as natural tracers in atmosphere and hydrosphere makes an important contribution to reconciling these different approaches.

Christian Leibundgut,
President, ITC

The quantification of the components contributing to flood discharges or to groundwater recharge has occupied hydraulic engineers for a long time. The increasing public interest on impacts related to extreme hydro-meteorological events leads also to a reassessment of the potential of isotopes as natural tracers in this field.

Variations of the isotopic composition of river or groundwater immediately following periods of intense precipitation or snowmelt are used since more than three decades, to identify different water components.

The snowcover in an alpine catchment is depleted in deuterium content as compared to the baseflow of the river which drains groundwater containing mean isotopic signal of the whole years precipitation. Rainstorms and snowmelt increase the discharge and trace the riverwater with the more negative isotopic signal. This allows to separate the groundwater component from direct runoff (shaded area) and express the latter in percent of the total discharge (upper part of the figure).

The different isotopic labelling can be used also to identify riverwater infiltration. In our illustrated example the groundwater between the rivers Danube and Iller is recharged from one or the other depending on the slope of the water table.

Water resources have a constant for any significance. Humanity has always been of too much of a problem somewhere. A study by the International Institute for Applied Systems Analysis (IIASA) to now there is no economic solution for this. Scientists are saying that we must use or the data to understand the impact of climate change on water supply.

An additional problem is water pollution resulting from industrial, agricultural and household activities. Water quality is often determined by the concentration of dissolved substances such as nutrients, heavy metals, and organic compounds. Monitoring water quality is crucial for assessing the impacts of human activities on aquatic ecosystems and ensuring the health and safety of water users.

The Rüttihubelbath recommended the inclusion of water quality data in existing monitoring programs for major rivers. What contributes may be the number of Rhine and Isar rivers with new isotopes reflect the pollution as observed in previous studies. Changes in regional water component groundwater ratio changes or glacier...

Water resources have never been constant for any significant length of time. Humanity has always faced the problem of too much or too little water somewhere. A study made by the International Institute for Applied System Analysis (IIASA) showed that up to now there is no consensus among scientists regarding the best technique to use or the data needed to model the impact of climate change on water supply.

An additional problem is self-made: Water pollution reduces available resources; developing countries have increasingly the pollution problems of modern agriculture, industry, and urbanization added to those arising from poverty and poor sanitation. GEMS-WATER aims to define, identify and quantify the status of freshwaters worldwide. WHYCOS is conceived as a tool for improving the collection, dissemination and use of high quality hydrological and related data at the national, river basin, regional and international levels.

The Rüthihuelbad workshop recommended the inclusion of isotope data in existing monitoring programmes of major rivers. What they are able to contribute may be illustrated by the examples of Rhine and Rhône. Stable isotopes reflect the warming trend as observed in precipitation on a regional scale. Changes in seasonality (reduced snow cover between 1989 to 1990) or dampening (Rhône water is artificially mixed by the production of hydro-electricity) are also apparent. Changes in regional runoff of different water components (the surface to groundwater ratio), evaporation changes or glacier meltwater contributions (altitude effect) may be included in the isotopic signal as well. Isotope time-series data of other components of the regional water cycle can help to disentangle these signals.
Precipitation is the variable at the interface between meteorology, climatology and hydrology. It is typically an output from meteorological and climatological analyses and an input to hydrological studies. Two fundamental questions in hydrology are:

- Where does a drop of water come from?
- Where does water evaporating from here go to?

Studies of the isotope composition of precipitation might help answer both of these questions.

Michel J. P. Jarraud,
Deputy Secretary-General, WMO

A pre-requisite for understanding the extent to which isotopic signatures can transfer the water cycle over evolutionary timescales is an understanding of how to interpret and use the data. Many short term climate models can be used to explore the future of the water cycle in different parts of the world. Over recent decades, several networks in Europe have been established to study the water cycle in detail. These networks have made it possible to collect and archive large amounts of data on precipitation and other hydrological variables. One of the purposes of the World Meteorological Organization is to promote activities in operational hydrology and to further close co-operation between Meteorological and Hydrological Services. Demands for the immediate assessment, development and protection of water resources are increasing in all parts of the world. Extreme hydrological events represent an important focus in the Hydrology and Water Resource Programme of WMO (HWPR). A better understanding of the relationship between climate and extreme hydrological events is of utmost importance. The possibility of an increase in frequency and severity of floods and droughts, soil erosion and changing groundwater tables due to anticipated global warm-
ing dominates the debates on sustainable development, and puts pressure on monitoring and research. The available historical and environmental proxies are too limited in space and time to provide clear answers. Therefore the possibility of extending the data base by isotope methods is of great interest for HWRP.

A pre-requisite is to know the extent to which isotopes in precipitation can transfer the signature of extreme events to other components of the water cycle where they may be archived.

Many short term case studies have shown the value of isotope methods in understanding hydrological extremes. For example the isotopic signature of storm events is often used for the separation of different water components and for establishing the extent to which they contribute to surface runoff or groundwater formation. Longer time series on a monthly basis, are currently available from several networks in Europe.

Our isotope example from alpine Switzerland illustrates the reaction of shallow groundwater to changing precipitation patterns. The monthly and seasonal deviations are related to the yearly means. Normal input - output conditions are characterized by a time lag of several months. Winter precipitation depleted in oxygen -18 discharges during the summer time in the spring water; summer infiltration during winter time. The time series of stable isotopes record seasonal changes in precipitation as well as changes in atmospheric temperature.

Between 1988 and 1990 the alpine region experienced three consecutive winters without snow cover. This was, at least on the historical time scale, an extreme event. It is clear from the illustrated results, that the isotopic composition of the groundwater recorded not only the warming, but also a distinct change in infiltration and recharge.
The Global Observing Systems

Global change science has become a prominent user of all kinds of available data sets. Separating production from consumption has not always improved digestion. GNIP has experienced this to some degree. The transformation of complex data like isotopic ratios in the water cycle into high quality science relies on a sound understanding of the processes involved. Only then can it lead to new insights in Earth system science.

Much effort is currently invested in ensuring long term observation and consistent data sets. Published reviews of the GNIP data have confirmed their coherence and value at the global, national and individual level.

Relationship between observing systems

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<thead>
<tr>
<th>ATMOSPHERE</th>
<th>LAND</th>
<th>OCEAN</th>
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<tbody>
<tr>
<td>WWW: World Weather Watch</td>
<td>GTOS: Global Terrestrial Observing System</td>
<td>GOOS: Global Ocean Observing System</td>
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<td>GAW: Global Atmospheric Watch</td>
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Global Climate Observing System

- Air pollution
- Ozone
- Weather
- Anthropogenic Impacts on Natural Systems
- Land Use Change
- Land Degradation
- Sustainability of Managed Ecosystems
- Water Resources Management
- Pollution and Toxicity
- Loss of Biodiversity
- Marine Services
- Coastal Zone Management
- Ocean Health
- Living Marine Resources

Climate is a driving force for Global Change. The Global Climate Observing System has been established to ensure that essential observations and information on climate-related issues are obtained and made available to the nations of the world. Its strategy includes the design and management of an effective operational system both by integrating and enhancing existing observations and by creating new data sets and observations in response to emerging needs.

The ultimate goal is to ensure the earliest possible detection of climate trends and climate change due to human activities.

Currently, the global observing systems in various processes: World Weather Watch, Global Atmospheric Watch and GOOS. These two systems ensure the atmospheric climate is monitored.

GAW, the Global Atmospheric Watch, serves as a system to detect further changes in the long-range transport of pollutants or dust particles. The water molecule on the earth dissolves and evaporates, and atmospheric convection can include isotopic trace elements from carbon, sulfur or water, study can lead to a better understanding of the behaviour of the atmosphere and biosphere.
Currently there are a series of global observing systems which are in various processes of development. World Weather Watch and Global Atmospheric Watch are already operational. These two systems together form the atmospheric component.

GAW, the Global Atmospheric Watch, serves as an early warning system to detect further changes in the atmospheric concentrations of greenhouse gases, changes in the ozone layer or in the long range transport of pollutants or dust particles. Water vapour dissolves and transforms various atmospheric constituents. These include isotopic tracers not only from the water molecule itself, but also from carbon, sulfur or nitrogen. Their study can lead to a better understanding of the behaviour of sources and sinks in the atmosphere, hydrosphere and biosphere.

The Rüttighubelbad and Vienna expert meetings recommended not only a close co-operation with GNIP reference stations, but also a joint GAW-GNIP research programme. This programme should link isotopes, cloud physics and atmospheric chemistry on time scales of hours to days and should also include analysis of the isotopic composition of water vapour and its relation to that in the precipitation derived from it.
The World Climate Research Programme (WCRP)

The World Climate Research Programme was established in 1980 to improve our knowledge of the physical controls of climate and of its variability. Water in all its phases is a major factor controlling climate. The WCRP activities have therefore been focussed from the beginning on the interactions between the oceans and the atmosphere.

ENSO, the combination of El Niño and the Southern Oscillation, a see-saw of alternating high and low pressure zones centered around Indonesia, influences weather and climate in many tropical and extra-tropical regions.

In certain years North America, Madagascar, Peru, India, Australia and even Europe have one thing in common: they are plagued by recurrent climate anomalies which have the same cause, El Niño. This Peruvian name for an ocean/atmosphere oscillation also symbolizes the first major success of TOGA, the Tropical Ocean Global Atmosphere project of WCRP. The El Niño phenomenon is the first climate anomaly for which the physical basis has become well understood. This knowledge is used today for seasonal to interannual climate predictions.

But the short which instrumental makes prediction le Isotopes again help t problem: Corss from a natural multivariat tem; oxygen-18 de biogenic carbonate re Temperature (SST) at

Therefore the project on ClimateVei ddictability (CLIVAR) paleoclimate compor it, through PAGES, i IGBP. The ultimate g project will be an u climate variability on tury time scales and i to predict - in so far a climate for one, or even ahead.

Isotopes shoul to another WCRP effc Global Energy and experiment. This programme in mechanisms control le radiation, clouds a ration, and freshwa fers another bridge b and IGBP, by co-ope programmes on Landtions in the Coastal Zoi on Biospheric Aspects logical Cycle (BAHC).
The combination of El Niño and the Southern Oscillation, a seesaw of alternating high and low pressure zones centered around Indonesia, influences weather and climate in many tropical and extratropical regions.

But the short time period over which instrumental data are available makes prediction less secure. Isotopes again help to overcome this problem: Cores from coral reefs offer a natural multivariate recording system: oxygen-18 deviations in the biogenic carbonate reflect Sea Surface Temperature (SST) and rainfall.

Therefore, the newest WCRP project, Climate Variability and Predictability (CLIVAR), will have a paleoclimate component, which links it, through PAGES, more closely to IGBP. The ultimate goal of this joint project will be an understanding of climate variability on decadal to century time scales and improved ability to predict, in so far as possible, climate for one, or even for several years ahead.

Isotopes should also be linked to another WCRP effort, GEWEX, the Global Energy and Water Cycle experiment. This programme investigates the mechanisms controlling processes like radiation, clouds and rain, evaporation, and freshwater storage. It offers another bridge between WCRP and IGBP, by co-operating with the programmes on Land-Ocean Interactions in the Coastal Zone (LOICZ) and on Biospheric Aspects of the Hydrological Cycle (BAHC).

GEWEX combines a number of continental or regional scale projects:

- **BALTEx (Baltic Sea Experiment)**
- **MAGS (Mackenzie River Basin GEWEX Study)**
- **GCIP (GEWEX Continental Scale International Project)** on the Mississippi River Basin
- **LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia)** and **GAME (GEWEX Asian Monsoon Experiment)**
Climate Change 1995:
The most recent IPCC report acknowledges that climate has not only changed in significant ways over the past century, but will continue to change, perhaps in dramatic and unpredictable ways in the future. There are still major uncertainties. Factors which seriously limit our ability to detect current and predict future climatic change are mainly related to uncertainties about future greenhouse gas emissions and their biogeochemical cycling.

Global Change is more than greenhouse gases, ozone holes, melting glaciers or polluted waters. In ways that are still poorly understood, humanity is altering virtually all the systems and cycles that together make life possible on Earth.

The International Geosphere-Biosphere Programme (IGBP) has been developed to improve our knowledge and to reduce uncertainties regarding the dynamics of global systems. Water is not only the solvent and conveyor for biogeochemical cycling and recycling processes; through its isotopic composition it provides an incredible, quantitative and versatile archive which we have only just begun to decipher.

Past global change research would be still in the Dark Ages without radioisotope-based chronologies and the stable isotope thermometer. By the same token, the basis for future prediction would be severely diminished.

In was in response to the need for sound and systematic baseline data changes, that PAGES the first core projects its task is to organize a palaeoscientific concerted effort to present quantitative reconstructions of Earth history. In order to address climate Change questions a series of terrestrial and marine tran
Climate has not only but will continue to the future. There are our ability to detect to uncertainties chemical cycling.

The study of past global changes provides the baseline data for IGBP, WCRP and IHDP. Important information is derived from isotope records of past precipitation as stored in natural archives like ice cores or lake- and ocean sediments. The isotope ratios of the water molecule offer opportunities to study atmospheric temperature, the origin of water vapour or atmospheric circulation patterns. These in turn are fundamental to the assessment of impacts due to changes in climate and the hydrological cycle.

Hans Oeschger, Past Chair, PAGES
There is a strong variation in the confidence and coherence with which stable isotope analyses are used in different types of paleoenvironmental archives.

At one extreme are ice cores and many deep sea sediments where the stable isotope records have been confidently interpreted in ways that have provided a coherent (though not necessarily uncontroversial) picture of reconstructed atmospheric or ocean temperature changes.

At the other extreme are records from lake sediments, peat bogs, and tree rings, for example, where problems of interpretation still loom large and the research as a whole lacks a unified approach.

The potential of stable isotopes as a quantitative tool for paleoscience is not questioned. In order to unfold the information on hydro-climatic parameters of the past, GNIP reference stations are of fundamental importance.

**Ice**
Condensation temperature, air mass source and sink conditions (temperature/relative humidity), airmass origin, amount of precipitation and its seasonal distribution.

**Tree rings**
Mixed physico-chemical and biological information on humidity and temperature; groundwater level, local water balance, air moisture, nutrients.

**Lake sediments**
Water temperature (surface-bottom), evaporation, hydrology in the recharge area (water balance, rapid events), productivity (biology, local environment).

**Ocean sediments**
Mixed physico-chemical and biological information on water temperature (surface-bottom), ocean circulation pattern.

**Corals**
Mixed physico-chemical and biological information on precipitation and sea surface temperature.

**Peat**
Temperature and precipitation, soil moisture, biological activity.

**Groundwater**
Temperature and precipitation, rapid events, infiltration and recharge conditions.

Quantitative interpretation requires the sensitivity of the instrument for precipitation and long-term fluctuation parameters.

High mountain environments are sensitive recorders of climate change. A notable exception is the glacial record from the Elbruz mountains, which provide evidence for environmental changes over the glacial cycles.

This is indeed an unprecedented human-induced effect superimposed on the natural climate variability.
Polar ice cores have proved to be a rich source of information about changes of climate in high latitudes during the last glacial cycle. The challenge for paleoscience is now to understand to what extent and by what processes these changes are mirrored in mid and low latitudes. The global expression of the Younger Dryas climate oscillation illustrates the high degree of interhemispheric coupling recorded in paleo-archives. This in turn emphasises the need for models capable of realistically answering the amplitude of future climate change in low latitudes where the majority of the human population lives, but also the power of paleo data to constrain such models.

Quantitative interpretation of isotope records preserved in continental archives requires a priori knowledge of the sensitivity of the isotopic composition of precipitation with respect to long-term fluctuations in key climatic parameters. High mountain environments are very sensitive recorders for detecting climate change. A meteorological station facing the glaciers of Mount Elbruz symbolize the potential for extending time series on climatic and environmental change beyond the limits of instrumental records. This is indeed an urgent need. Any human-induced effect on climate will be superimposed on the background noise of natural climate variability.

"The balance of evidence suggests a discernible human influence on global climate."

IPCC 1995, Policymaker Summary
“When you can measure what you are talking about, and express it in numbers, you know something about it; when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind.”

William Thompson Kelvin
- "Stable Isotope Hydrology: Deuterium and Oxygen-18 in the Water Cycle"

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  K. Rozanski, L. Araguás-Araguás and R. Genestani, in Geophysical Monograph 78, American Geophysical Union 1993

- Key-note lectures, Rüttihelbad:
  «Deuterium and Oxygen 18 in present-day precipitation - Data and modeling»
  J. Jouzel, K. Fröhlich and U. Schütterer
  «Reconstruction of Past Climates from Stable Isotope Records of Paleo-Precipitation preserved in Continental Archives»
  K. Rozanski, S.J. Johnson, U. Schütterer and L.G. Thompson
  «Extreme Hydrological Events, Paleo-Information and Climate Change»
  J.C. Knox and Z.W. Kundzewicz
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- Report of the international workshop on
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  Rüttihelbad near Bern (Switzerland), 23-25 January 1995
  WMO, Geneva 1995
  «Operational Aspects of the Global Network for Isotopes in Precipitation»
  Consultants meeting, Vienna (Austria), 7-10 November 1995
  IAEA, Vienna 1996

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p.27: North Atlantic Oscillation; J. Hurrel, NCAR, Boulder
p.29: Models: G. Hoffmann, MPI for Meteorology, Hamburg
p.34: Component separation: W. Stichter, GSF-Institute for Hydrology, Munich
p.41: Corals: J. Cole and R. Dunbar, University of Colorado

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