

**CONCLUSIONS OF THE  
WORKSHOP ON ION-AEROSOL-CLOUD INTERACTIONS  
CERN, 18-20 APRIL 2001**

**Executive Summary**

Recent observations suggest that cosmic rays may play a significant role in the climate. In particular, satellite data have revealed a surprising correlation between cosmic ray intensity and the fraction of the Earth covered by low clouds. Since the cosmic ray intensity is modulated by the solar wind, this could provide an important clue to the long-sought mechanism connecting solar and climate variability. Moreover, if this connection were to be established, it could have significant consequences for our understanding of the solar contributions to the present global warming, since the cosmic ray intensity has fallen during the 20<sup>th</sup> century due to a more-than-doubling of the strength of the solar wind.

In order to test whether cosmic rays and clouds are causally linked and, if so, to understand the microphysical mechanisms, a novel experiment known as CLOUD has been proposed at CERN by an interdisciplinary collaboration of atmospheric, solar-terrestrial, cosmic ray and particle physicists. CLOUD proposes to use a CERN pion beam as an artificial source of cosmic rays. The beam would pass through an expansion cloud chamber in which the atmospheric conditions within clouds throughout the atmosphere could be reproduced. All parameters of the experiment would be precisely controlled and measured.

A workshop was recently held at CERN to discuss the scientific case for a connection between cosmic rays and clouds, and to review the proposed CLOUD facility. The outcome was a clear consensus that the scientific indications of a cosmic ray-cloud link are both interesting and important, and that plausible microphysical mechanisms exist but their significance is not yet known. There was unanimous agreement on the urgent need to perform controlled laboratory measurements to test the cosmic ray-cloud link in a particle beam at CERN, as proposed by the CLOUD experiment. Further details on the outcome of the workshop are provided below.

## **I. Introduction**

The European Geophysical Society, the European Physical Society and the European Science Foundation co-sponsored an inter-disciplinary “Workshop on Ion-Aerosol-Cloud Interactions” at CERN, 18-20 April 2001. The workshop was attended by about 50 physicists representing 14 countries and drawn from the atmospheric, aerosol, palaeoclimatological, solar-terrestrial, cosmic ray and particle physics communities. This aim of the meeting was twofold:

- 1) To review the present knowledge of ion-aerosol-cloud interactions and their possible role in solar-climate variability.
- 2) To review the proposed CLOUD Atmospheric Research Facility using a particle beam at CERN.

## II. Procedure

In order to arrive at a consensus on the workshop conclusions, the meeting closed with a “Workshop Summary Panel” discussion. The panel members comprised:

Sir Arnold Wolfendale /University of Durham (chairman)  
Mike Lockwood /RAL, President of Solar-Terrestrial Sciences, EGS  
Maurice Jacob /Chairman of the Joint Astrophysics Division of EAS and EPS  
Richard Turco /University of California, Los Angeles  
Paul Wagner /University of Vienna

To focus the discussion, the chairman presented four basic (but inevitably over-simplified) questions to the panel and then to the floor:

- 1) “Does cosmic ray ionization play a role in the climate?”
- 2) “Is the mechanism: ionization -> aerosol -> cloud understood?”
- 3) “Is the case (scientific motivation) for a cosmic ray influence on cloud cover agreed?”
- 4) “Would the CERN ‘CLOUD’ facility satisfy a need?”

As well as a general discussion, the chairman invited all those present (numbering about 30 in the final session) to vote either “No”, “?” or “Yes” to each question. Finally, after each question had been discussed and voted in turn, the chairman invited the panel and floor to express their opinions on a fifth question:

- 5) “Why at CERN?”

The points raised during the discussion on each question are summarised below, together with the results of the voting.

## III. Responses to the questions

### 1) “Does cosmic ray ionization play a role in the climate?”

**Elaboration:** This question asked whether cosmic rays have the *potential* to affect the climate and whether there is evidence that it may be happening. The question did not ask whether cosmic rays do indeed significantly affect the climate - which is clearly unanswerable at present.

**Discussion:** Clear historical correlations of sunspot/solar variability and changes in the Earth's climate were presented at the workshop. For example, Beer, Lockwood and van Geel showed examples such as the Maunder Minimum (Little Ice Age), the circa-850BC climate anomaly and the Younger Dryas cold event at the end of the last Ice Age (12.9-11.6 kyear before present) which are associated with solar variability as revealed in the sunspot record and in the cosmogenic isotope record in ice-cores ( $^{10}\text{Be}$ ) and tree-rings ( $^{14}\text{C}$ ). These data directly indicate the prevailing galactic cosmic ray (GCR) intensities, which are modulated by the solar wind (and by slower changes in the Earth's magnetic dipole). However the solar/GCR-climate correlations are sometimes present and sometimes not. This may reflect

the complexity of the Earth's climate - that many factors are important and they interact in a complex way. The climate may have stable states such that a correlation may persist for some decades and then disappear for a while. In addition, whatever caused those earlier natural climate shifts may also be interacting with today's anthropogenic contributions in the atmosphere to produce a yet more complex response, for example anthropogenic sulphur dioxide and its effect on cloud cover.

However, correlations do not demonstrate cause and effect, so the present data are unable to separate whether the Sun-Earth coupling is via electromagnetic radiation (total irradiance/UV/...) and/or via energetic cosmic rays (galactic/solar). But it is important to note that these are the only possible vectors (it is unlikely that the solar wind itself could be directly responsible) - and so at least one of them must be implicated. In the case of cosmic rays one should in particular study and understand the amplification factors that would be necessary to enhance their role despite their very small energy input (roughly equivalent to that of starlight) in comparison with total solar irradiance. (The vast disparity of energies, by itself, does not exclude the possibility of an effect; there are numerous examples in physics of large energy amplification factors, such as a nuclear chain reaction released by a few initial neutrons.)

In the case of the current global warming, there is increasing agreement that the climate model fits to the temperature record need to amplify the solar contribution by about a factor 3. The presently-assumed solar contribution is only from the (Lean et al., 1995) direct irradiance changes. An additional, indirect, solar contribution could either decrease or increase the projections of the anthropogenic effects. (The latter possibility arises since an increased solar attribution during the last century could indicate a steeper anthropogenic rise in recent decades.)

The satellite data analysis presented at the workshop by Svensmark indicates a solar cycle correlation with low cloud cover, suggesting that the solar-climate mechanism may involve clouds. Again, at this stage both electromagnetic radiation and GCRs remain as candidates. This may provide the first clue to the long-sought amplification mechanism linking solar and climate variability. However the underlying processes may involve subtleties since the observed solar correlation is confined to low clouds, and the global correlation map of low cloud cover shows no preference for high geomagnetic latitudes – both of which appear to be counter-intuitive at first sight.

***Vote:*** The distribution of votes on the question “Does cosmic ray ionization play a role in the climate?” was equally divided between “?” and “Yes”, with zero votes for “No”. This implies that there are reasonable indications that cosmic rays have the potential to affect the climate but that the question of whether they are significant is far from settled.

## **2) “Is the mechanism: ionization -> aerosol -> cloud understood?”**

***Elaboration:*** This question asked whether there is any microphysical understanding of the mechanism(s) by which cosmic ray ionization could affect 1) the nucleation of new aerosol and 2) the lifetime, albedo or other properties of clouds.

**Discussion:** There is now strong evidence to support the existence of the first step. Yu and Turco presented the results of their theoretical studies of ion-induced nucleation and conclude that ions play an important role in the creation and early growth of ultrafine condensation nuclei (UCN) from trace vapours such as sulphuric acid. These frequently occur in clean environments (such as over oceans) at very low concentrations where classical nucleation theory predicts no nucleation should occur - but nevertheless nucleation is observed. Yu and Turco find that the presence of charge serves to stabilise the embryonic clusters, and their ion-mediated model agrees with the experimental observations. In addition, Yu reported on the effect of variations of GCR ionization at different altitudes and concludes that it can be the limiting factor to aerosol nucleation at low altitudes, whereas at high altitudes, where the ionization rate is up to a factor 20 larger, other parameters such as the trace gas concentrations become the limiting factor. This would provide a possible explanation why the solar modulation is observed only in low clouds.

As well as theoretical developments, F. Arnold presented at the workshop the first direct observation of ion-induced nucleation in the laboratory, and also aircraft measurements of the ion mass spectrum in the atmosphere which extend to large ions and indicate the presence of ion-induced nucleation.

These theoretical and experimental developments represent significant progress and lay to rest a common criticism raised against the cosmic ray-cloud hypothesis - namely that no microphysical mechanism exists to connect cosmic rays to clouds. At least one mechanism exists but whether or not it is significant is not yet known. Whereas there now seems little doubt that cosmic rays can influence the nucleation of trace condensable vapours under certain conditions, the effect of these extra UCN on the cloud condensation nuclei (CCN) that seed cloud droplets is an open question. Equally, the influence of GCRs on the growth process of other aerosols or on the activation of CCN into droplets is not known. However, if cosmic rays could indeed modify the CCN number concentration in certain regions of the atmosphere then this may affect both cloud lifetimes and albedo. Furthermore, GCRs may have other effects on clouds such as the electrofreezing of supercooled liquid droplets, influences on the global electrical circuit and electric field strength, and the production of trace reactive chemicals (NO, OH) which could affect atmospheric chemistry at certain altitudes. In summary, there are now actually several mechanisms that have been identified by which GCRs may potentially affect clouds, but they are yet to be investigated experimentally and quantified.

**Vote:** The distribution of votes on the question “Is the mechanism: ionization -> aerosol -> cloud understood?” was bimodal. There was a 100% “Yes” vote for the first step, indicating that at least one mechanism is explicable theoretically, if not proven experimentally (although the first direct observations of ion-induced aerosol formation were presented at the workshop). However whether or not these UCN have a significant effect on CCN is essentially unknown. This was reflected in the vote for the second step which was equally divided between “No” and “?”, with zero votes for “Yes”. This latter vote indicates also the poor experimental and theoretical understanding of the effects of ionization on the aerosol growth and activation processes, and on other areas where it may play a role.

**3) “Is the case (scientific motivation) for a cosmic ray influence on cloud cover agreed?”**

*Elaboration:* This question asked whether the scientific indications are sufficiently interesting and important to merit a controlled laboratory experiment on the influence of cosmic rays on clouds.

*Discussion:* In view of the preceding discussion on the first two questions, there was little extra discussion before a vote was taken on this third question. However it was pointed out that the GCR-cloud hypothesis may be the very first hard clue we have as to what is behind the solar-climate correlations that have been observed over the last two centuries. If our only tool is correlations, we may continue another two centuries and still not be able to understand the underlying mechanism. However at last we have a definite hypothesis that can be tested experimentally: “Are cosmic rays affecting cloud formation?”. The question is so important that we should pursue it.

*Vote:* On the question “Is the case (scientific motivation) for a cosmic ray influence on cloud cover agreed?”: 100% “Yes”.

**4) “Would the CERN ‘CLOUD’ facility satisfy a need?”**

*Elaboration:* This question asked whether the CERN ‘CLOUD’ facility would provide important new experimental data on the subject of ion-aerosol-cloud interactions and whether the facility would be complementary to other experiments in this field.

*Discussion:* It was agreed that the CLOUD facility is timely for several reasons. First of course are the recent satellite observations of a solar modulation of cloud cover, and its possible effect on the climate and global warming. Recent theoretical progress has been made on the understanding of ion-mediated effects on aerosols by Yu, Turco, Okuyama and others, and there is now an urgent need for experimental data to test these models. Finally, it is only in the last few years that the necessary precision experimental tools have been developed which will allow the proposed CLOUD experiments to be carried out.

At the workshop Möhler presented the experience with the Karlsruhe aerosol chamber facility, AIDA, which has successfully demonstrated the feasibility of aerosol growth experiments in the laboratory under atmospheric conditions. Furthermore Wagner described recent measurements which show expansion cloud chambers to be versatile and high-precision experimental tools that are ideally suited for the proposed studies. With expansion cloud chambers, well-defined thermodynamic conditions can be produced over large volumes and, with the use of a CERN particle beam, the cosmic ray conditions throughout the atmosphere can be recreated. The proposed CLOUD facility would be the world's first to precisely simulate the conditions inside clouds at all altitudes and latitudes, and to investigate the effects of ionizing particle radiation on aerosol and cloud processes.

In addition to aerosol nucleation, growth and activation experiments, CLOUD will be able to measure the effect of cosmic ray ionization on a wide range of atmospheric processes. For example, Carslaw described at the workshop how ionization has been proposed as the

possible mechanism by which polar stratospheric clouds freeze. Discovery of the freezing mechanism in these clouds is crucial to our understanding of de-nitrification and subsequent ozone loss over the poles. Kellett showed evidence for production of nitric oxide in the atmosphere by energetic solar cosmic ray events and suggested that GCRs may affect the rate of NO production in the lower atmosphere by affecting lightning production. Stozhkov in fact presented ground-based data collected in some regions of the United States that shows a correlation between the GCR intensity and the frequency of lightning. Stozhkov also suggested that a preferential activation of water droplets on negative ions may be responsible for charge separation in clouds, and therefore lightning. He also presented data indicating a decreased rainfall during Forbush decreases, and increased rainfall during energetic solar cosmic ray events. GCRs are responsible for the fair weather ionization throughout most of the lower atmosphere and are therefore a key element in the global electrical circuit. Harrison summarised several atmospheric electricity processes, such as electrofreezing, aerosol charging, and the scavenging of charged aerosols by cloud droplets, that may play important roles in cloud microphysics.

The CLOUD facility can investigate the fundamental physics that underlies each of these processes. It would provide important microphysical measurements to help the interpretation of atmospheric observations by programmes such as the ESF SPECIAL network to study Sun-Earth links, which Rycroft described at the meeting. In short, there is not a single “need” for CLOUD but, rather, a wide range of “needs”, making the concept of a facility appropriate for the project. Furthermore, CLOUD should be seen as providing an essential and complementary contribution in support of an extensive on-going solar-terrestrial experimental programme involving satellites and ground-based stations.

**Vote:** On the question “Would the CERN ‘CLOUD’ facility satisfy a need?”: 100% “Yes”.

##### **5) “Why at CERN?”**

**Elaboration:** This question asked why the CLOUD facility should be located at CERN.

**Discussion:** There are two basic reasons why CERN is uniquely suitable for the CLOUD facility: a) the particle beam and b) technological expertise and excellence in the equipment needed for the experiment, together with rapidly-increasing knowledge by talented staff of the detailed research problems to be addressed.

The theoretical studies of Yu, Turco and others have shown that ionization effects are highly non-linear and so experiments must reproduce ionization rates and ionization densities ( $dE/dx$ ) close to natural GCRs. Such measurements have so far never been achieved with radioactive sources despite experiments over the last 40 years. However, a CERN pion beam closely duplicates natural GCRs and provides a precisely controlled and delivered particle ionization inside the active volumes of the experiment.

To answer the scientific questions addressed by CLOUD requires a sophisticated and technically-challenging experimental apparatus - one that is beyond the capabilities of individual institutes but well within the scope of the experiments for which CERN is well

known. In particular CERN has key expertise in the expansion cloud chamber, from its experience with BEBC and other bubble chambers. In this sense the CLOUD facility could be considered as a “technology transfer” from CERN, but to another research community rather than to industry, and on a subject of great interest to society. The project represents a unique interface that brings together cosmic ray/particle physics - which is within the mandate of CERN - and atmospheric physics. Such a facility may attract EU funding support. The facility coincides with a research hiatus at CERN over the next 5 years while the LHC is being constructed.

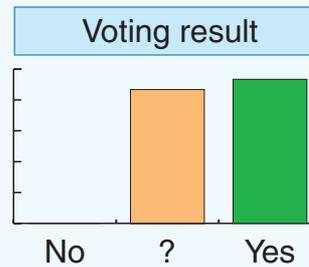
As well as issues related to the beam and technological expertise, the CLOUD facility has attracted an enthusiastic interdisciplinary collaboration with an unprecedented range of experience and skills.

However, the prime reasons “Why at CERN?” are the importance of the CLOUD facility to science and to society; and CERN is the unique host.

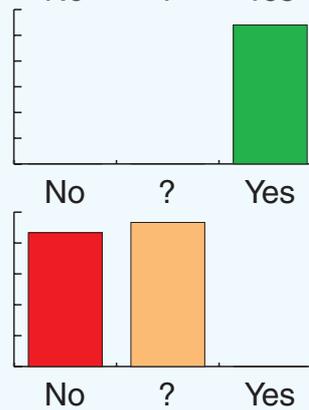
Chairman of the IACI Workshop Summary Panel  
**Sir Arnold Wolfendale, FRS**  
University of Durham

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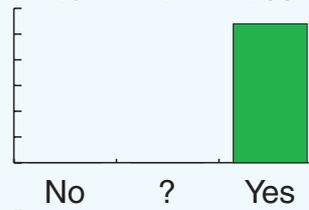
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2) "Is the mechanism understood for:  
a) ionization -> aerosol?  
and  
b) aerosol -> cloud?"



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