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The Global Energy and Water Cycle

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The Global Energy and Water Cycle

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Next July the European Conference on the Global Energy and Water Cycle is being held in London at the Royal Society. The deadline for abstracts is not far away (see announcement on page xx) and so it is perhaps timely to write a few words about this general topic.

Water in all its forms is the life-blood of the climate system. As water vapour it is the principal contributor to the greenhouse effect. As cloud it dominates the planetary albedo and the radiative energy available at the surface of the earth. The balance between precipitation and evaporation controls the availability of freshwater at the ground and its supply to living material. By affecting the salinity of the ocean surface it also influences the circulation of the ocean. The global water cycle is a key component of the energetics of the earth system through atmospheric transport, latent and radiative heating, and through redistribution of water over the surface.

Scientifically this is a multiscale and multidisciplinary subject offering an enormous challenge. It brings together meteorologists, hydrologists, oceanographers and others in the study, via observations, modelling and theory, of mechanisms on scales ranging from the global circulation to small scale processes whose effects are felt both regionally and globally. It is a growing field of research internationally, with major activities coordinated by the World Climate Research Programme (WCRP) and by the International Geosphere-Biosphere Programme (IGBP). The largest concentration of effort in this field is within WCRP's Global Energy and Water Cycle Experiment (GEWEX). Liaison across related activities in the UK is achieved within the Royal Society's GEWEX Forum. We now give a flavour of some of the key issues and UK activities.

Clouds are a topic in which the UK has a long tradition of research. Activities are now moving towards the development of improved methods of modelling and observing clouds in ways that address their global impact. A world-class boundary layer model developed in the Meteorological Office is being adapted and used by scientists at the Joint

Centre for Mesoscale Meteorology at Reading University and at UMIST for studying ensembles of clouds. This research will contribute to the goal of the international GEWEX Cloud System Study which aims to use such cloud-resolving models to develop improved ways of parametrizing the effects of cloud processes (Fig 1) within global general circulation models (GCMs).

One of the greatest impediments to understanding the radiative effects of clouds is our ignorance of their vertical distribution. Clouds with different vertical distributions produce different vertical profiles of atmospheric heating (Fig 2). Such differences have a substantial effect on the performance of GCMs and vertical cloud profiles need to be measured globally in order to develop and validate the GCMs. Space missions planned as part of the Earth Observing System will not provide the necessary information on vertical cloud profiles and so GEWEX attaches top priority to the development of a millimetre-wave spaceborne radar. The Rutherford Appleton Laboratory is currently managing a feasibility study of such a system, with inputs from scientists and engineers in several UK universities, industry and government agencies. The results will contribute to a concerted activity involving two or more space agencies.

Observing problems are not restricted to the clouds themselves. Despite its known importance in many climate processes, the global distribution of the resulting precipitation is also very poorly observed. No single measurement technique offers anything like a complete solution. The Global Precipitation Climatology Project (GPCP) aims to develop the best possible climatology of precipitation using a combination of available satellite and ground based measurements and numerical weather prediction models. The UK recently hosted the Algorithm Intercomparison Project (AIP)-2 under the auspices of GPCP. The purpose of AIP-2 is to develop a precipitation data set against which to test various algorithms for estimating surface precipitation using microwave radiometer measurements from polar orbiting satellites and infra-red measurements from geostationary satellite. Scientists from the Universities of Bristol and Reading were involved, amongst others. The inference of surface precipitation from passive radiometers can be confused by the vertical structure of the precipitation, for example, the presence of ice particles aloft. The understanding of the satellite observations is being aided by polarization measurements from the multiparameter radar at Chilbolton, Hampshire (Fig 3). Especially when used together with *in situ* measurements from the C-130 aircraft of the Meteorological Research Flight, these radar measurements provide an indication of the 3-D distribution of precipitation type.

Another weak link in the global measurement capability relates to water vapour. Measurements with the required vertical resolution and accuracy will not be available globally until a new generation of satellite instruments has been developed. In the meantime a significant improvement in water vapour measurements will result when the Advanced Microwave Sounding Unit (AMSU)-B developed by the Meteorological Office is flown on a NOAA weather satellite in 1996. To produce coherent data sets from incomplete observational data such as these it is necessary to use short-range weather forecast models. In this approach the models assimilate a variety of data in time and space (4-D Data Assimilation) to provide a 6-12 hour forecast. This can then be used to construct a complete and self-consistent global description of the observed state. It can also be used to transport information from data-rich to data-poor areas, and to make estimates of parameters (eg surface fluxes) not directly measured. By this means operational activities at Weather Services such as the Meteorological Office and the European Centre for Medium Range Weather Forecasts (ECMWF) will make a crucial contribution to research into climate processes.

Despite the fact that water vapour is a key ingredient in its feedback on atmospheric motion, weather and climate, it is only recently that the routine analyses performed daily in Weather Services have begun to contain useful data on its distribution. Indeed, until recently, the real distributions of water vapour were often inconsistent with the requirements of the representations of deep convection and other processes in the models. Figure 4, obtained by researchers at the University of Reading, is evidence that the situation is now changing. The figure shows previous climatological estimates of the difference between evaporation and precipitation as a function of latitude determined on the basis of local station data. It also shows estimates of this quantity determined from the convergence and divergence of water vapour computed from 4 years of model analyses produced by ECMWF. The agreement between the estimates of this fundamental quantity supports the idea that it is now opportune to give much increased consideration to the role of water vapour in the large-scale circulation of the atmosphere using the analyses from forecast centres, as well as any independent data that may be available. Such studies will give a basis for assessing the performance, and hence improvement, of climate models in probably their weakest area - the parametrization of moist processes. To do this properly, existing theoretical frameworks for viewing the moist circulation of the atmosphere must be exploited and the possibility of new ones must be studied.

Energy and water exchanges are particularly important at the interfaces between the atmosphere and sea, ice and land surfaces. Air-sea interaction is important to understanding the global water and energy budget because the ocean can store and transport heat and freshwater, releasing them to the atmosphere at locations and times different from those at which they entered. The ocean circulation is itself controlled by the surface fluxes of heat and water as well as momentum (see Fig 5). However, knowledge of the fluxes over the global ocean, in particular their spatial and temporal distribution, is poor. For climate purposes, the accuracy requirements for surface fluxes are very stringent. For example, sea surface temperature - a key variable in the computation of surface fluxes - should be measured with an absolute accuracy of 0.3K. Although many of the relevant parameters have been measured to high accuracy from surface platforms in carefully planned research experiments, it is not practicable to do this routinely on large space scales. Earth observing satellites such as Europe's ERS-1, which has operated successfully since July 1991, offer considerable potential in that sensors provide data from large areas of ocean in a relatively short time with more uniform coverage than surface-based systems. However, some vital parameters cannot yet be reliably determined from space alone. A further source of flux information, as described above, is the analysis phase of operational numerical weather prediction models, particularly if the quality of the data available to the models can be improved. The best fields of surface flux are likely to come from suitable combinations of *in situ* measurements, satellite data and models; it has also been proposed that ocean budget techniques could play a valuable role in calibrating the flux estimates.

Energy and water exchanges at the land surface are important because the possible changes in man-made climate forcing originate there, and it is at the land surface where the human impacts of possible climate change are apparent. There are many difficult questions to be answered in deciding how the land surface interacts with the atmosphere, on daily, seasonal or interannual time scales. The questions become more complicated at longer time scales, as vegetation grows, or even as plant communities change in response to different climates. A further problem is then in making reasonable predictions of the behaviour of this interaction under climate conditions different from those in which the observations have been made. Climate predictions are usually made using GCMs, but these average the processes spatially and can represent processes only simply. Thus new formulations are needed to represent the land surface processes both simply and realistically, at large spatial scales. Observations of the land surface are available from space systematically for the first time, and ways must be developed for using them along with the more conventional surface observations to constrain the GCMs. An example of current research in this area is the Hapex-Sahel experiment. Scientists from the UK along with colleagues from France, the Netherlands and the United States are attempting to understand how to scale-up land surface observations, specifically at the southern boundary of the Sahara Desert, and how the relative importance of different processes changes across the desert boundary. This will help them predict if dryland degradation would occur in a changed climate.

Until recently little attention had been given to considering how the redistribution of water at the land surface or underground could be represented in GCMs. Indeed many hydrological catchments are of an area that is smaller than the area of a single grid cell in a typical GCM. The hydrological community are therefore having to consider "scaling up" if their models are to provide an input to the GCMs. The meteorologists, on the other hand, who work with large complex models, are forced through computational limitations to operate on a course grid scale but seek to move to finer scales, ie they wish to "scale down". Indeed the atmospheric modellers may need to disaggregate their outputs if they are to be of value to the hydrological community, eg some spatial detail needs to be given to a GCM rainfall field. Figure 6 shows in simplistic form the "aggregation" and "disaggregation" processes that are needed in order to link the atmospheric and hydrological models. This is a newly emerging area of science and there are many scientific and technical problems to overcome before full integration of the atmosphere and hydrological models can be achieved at a macro scale. To advance this integration the GEWEX Scientific Steering Group established a GEWEX Continental Scale International Project (GCIP). The GCIP science plan established the need for a large basin study to provide the framework for the incorporation of the hydrological models into a GCM. The Mississippi Basin was selected for the first study (from candidates including the Nile, Amazon, Rhine and Danube) since the Mississippi has long time series of detailed hydrological and meteorological data. These are required so that models can be rigorously validated. The UK hydrologists and meteorologists have assisted in drafting the Science Plan for GCIP and have become involved in the emerging science programmes.

It should be clear from this article that the task of understanding the global energy and water cycle is so multifaceted and so challenging that it must be addressed by means of a well coordinated long-term programme of research which may extend well into the next century.

Figure captions

Fig 1	Cloud processes that need to be parametrized in GCMs, (a) radiative processes, (b) other processes. (Courtesy, P R Jonas,, UMIST).
Fig 2	Greatly differing vertical profiles of infra-red heating of the atmosphere by a complete overcast of cloud with top at 125 mb, depending on the height of the cloud base. (Courtesy, A Slingo, Met Office).
Fig 3	Vertical section through a thunderstorm obtained with the Chilbolton multiparameter radar. Reflectivity (in bottom picture) shows thunderstorm centred at 35 km and light snow above a highly reflective melting band elsewhere. Differential reflectivity (in top picture) shows very large raindrops in the yellow region. (Courtesy, A Illingworth, JCMM, Univ of Reading).
Fig 4	Estimates of annual evaporation minus precipitation (E -P) as a function of latitude. Previous estimates from station data are shown by the triangles and squares. A new estimate from 4 years of ECMWF analyses is shown by the continuous line. Note that 1000 in the units is equivalent to 1 m of water in a year, or about 3 mm per day. (Courtesy, J Dodd, Univ of Reading).
Fig 5	Schematic of the factors at the surface of the ocean that control the ocean circulation. (Courtesy, T Guymer, James Rennell Centre).
Fig 6	Schematic showing links between hydrological and atmospheric models. (Courtesy, W B Wilkinson, Inst of Hydrology).

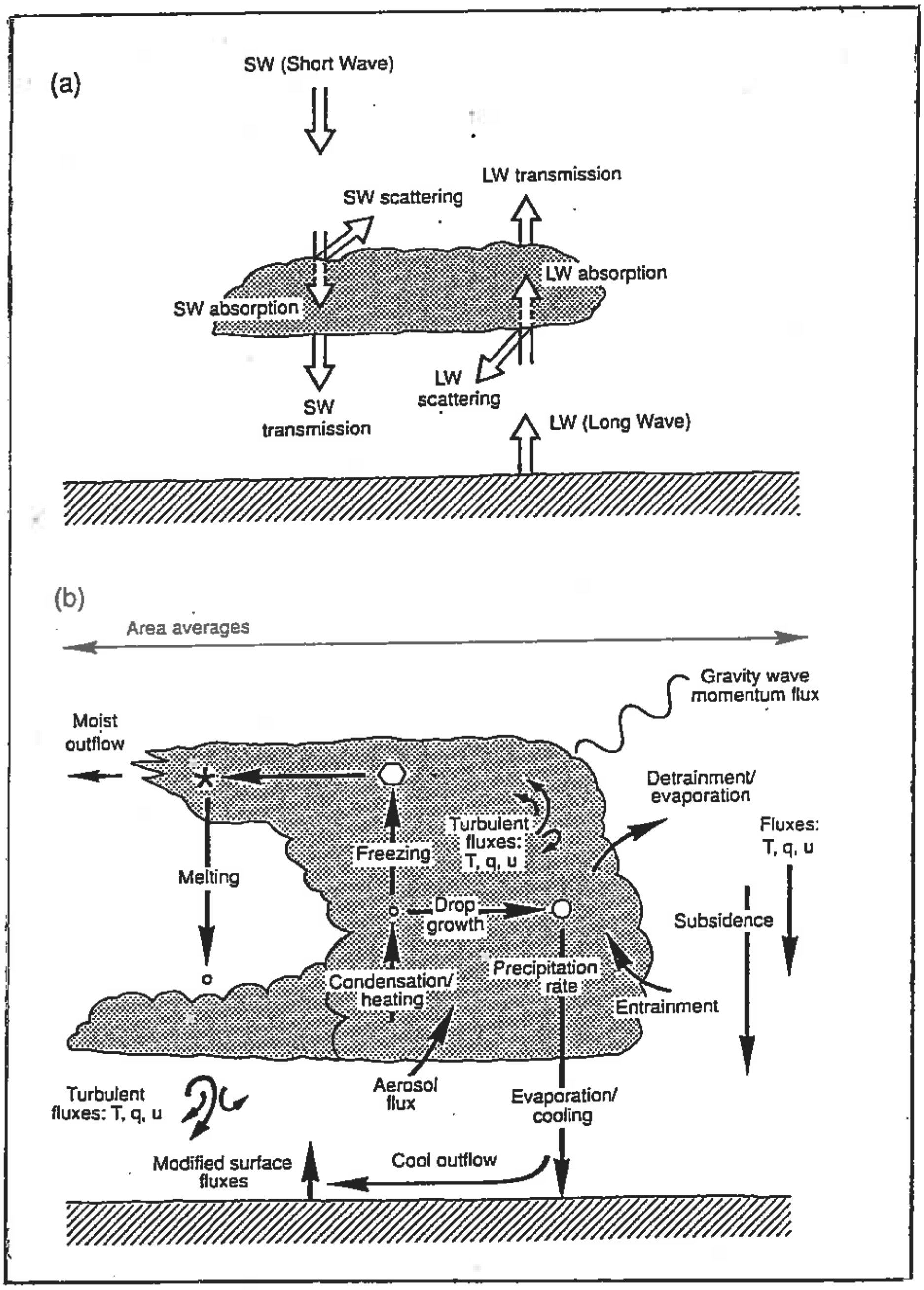
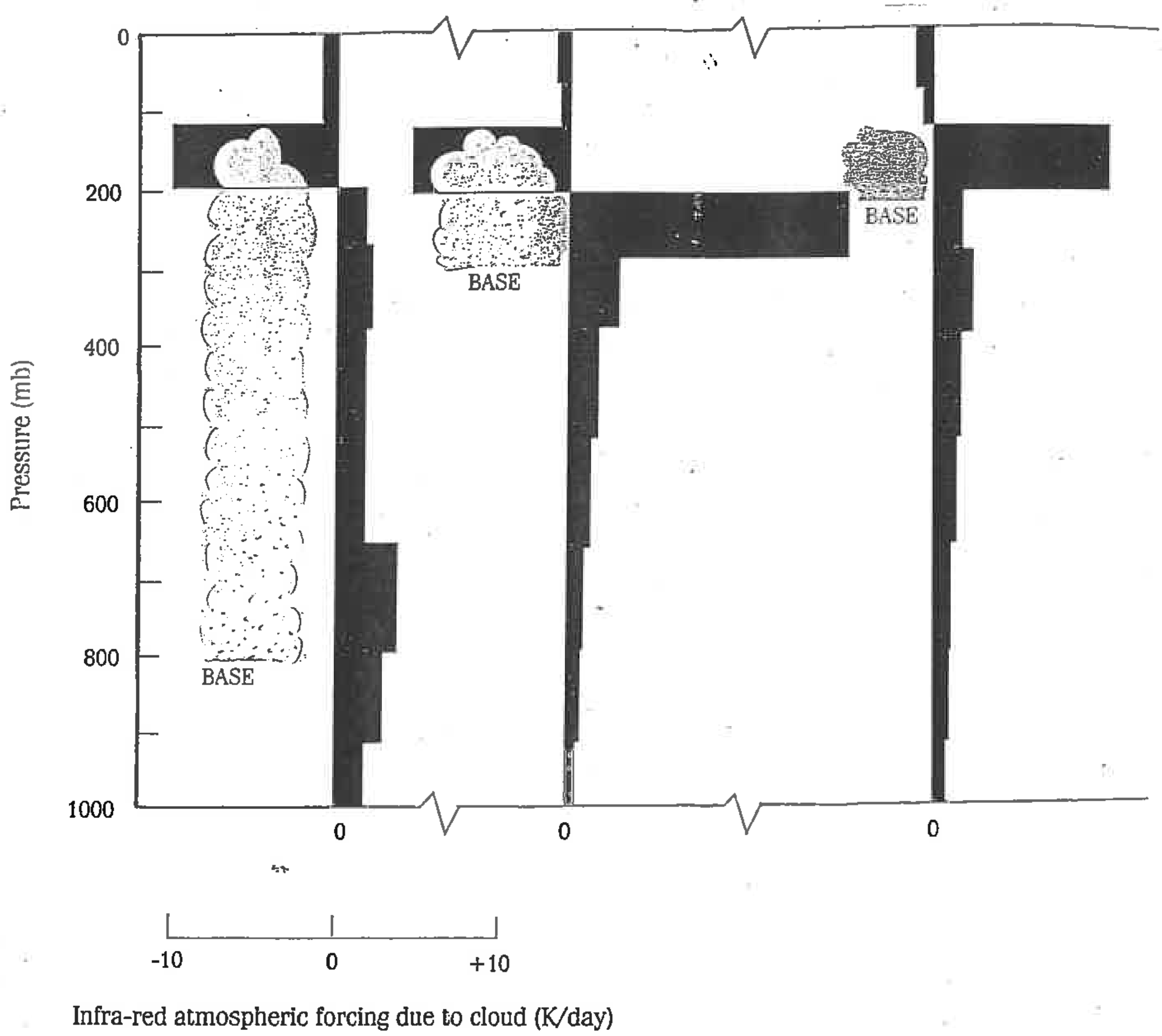

(a)
SW (Short Wave)
LW transmission
SW scattering
LW absorption
SW absorption
SW
transmission
LW
scattering
LW (Long Wave)
(b)
Area averages
Gravity wave
momentum flux
Moist
outflow
Detrainment/
evaporation
Turbulent
fluxes:
T, q, u
Freezing
Fluxes:
T, q, u
Melting
Drop
growth
Subsidence
Condensation/
heating
Precipitation
rate
Entrainment
Turbulent
fluxes: T, q, u
Aerosol
flux
Evaporation/
cooling
Modified surface
fluxes
Cool outflow

Fig 1



0
200
400
600
800
1000
Pressure (mb)
BASE
BASE
BASE
0
0
0
-10
0
+10
Infra-red atmospheric forcing due to cloud (K/day)

Fig 2

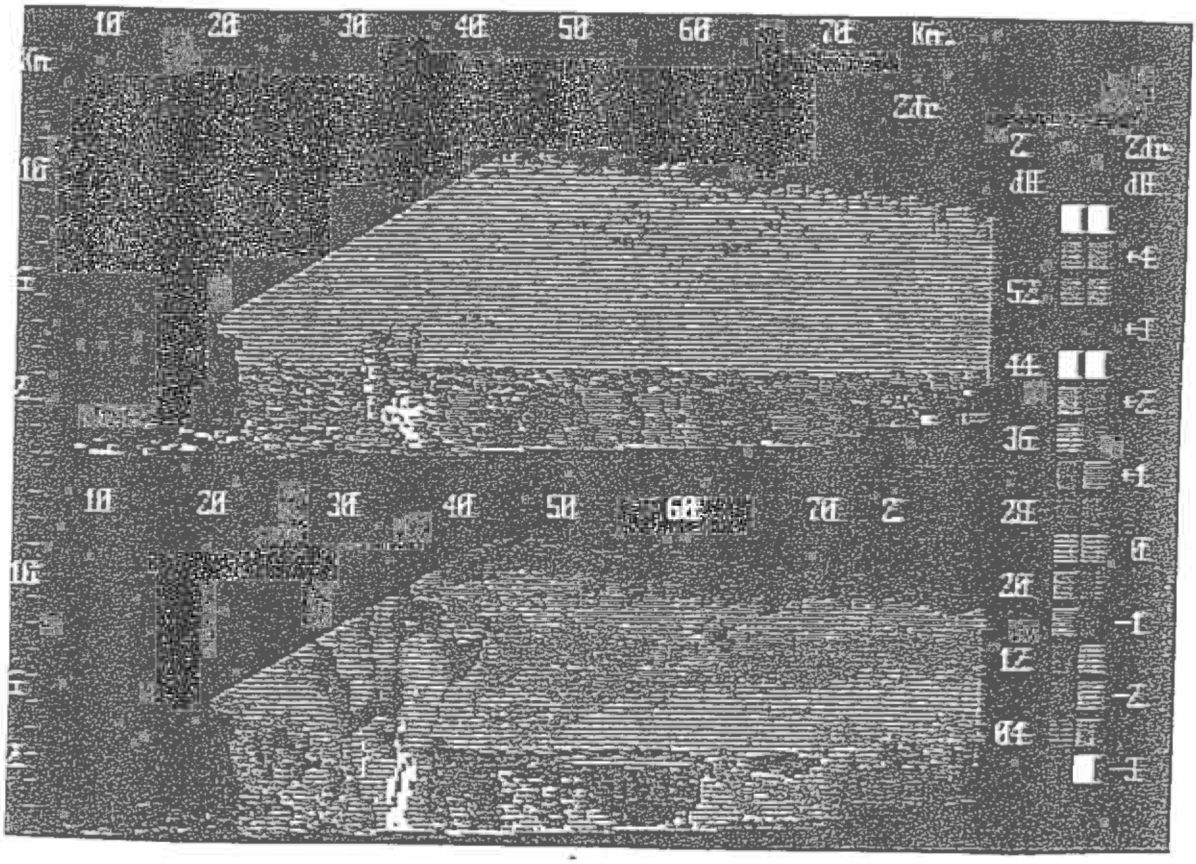


Fig 3

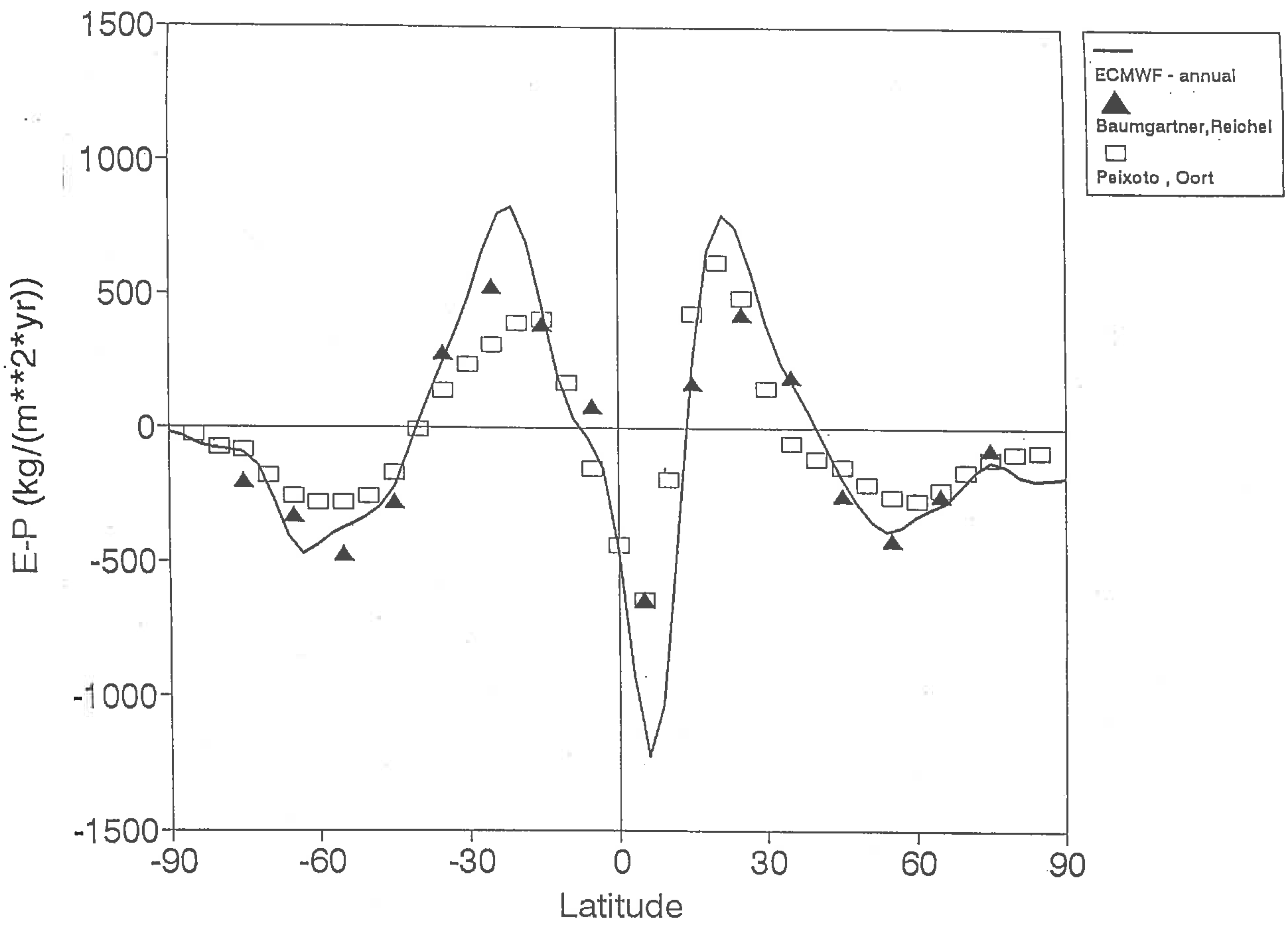

E-P (kg/(m**2*yr))
1500
1000
500
0
-500
-1000
-1500
-90
-60
-30
0
30
60
90
Latitude
ECMWF - annual
Baumgartner,Reichel
Peixoto , Oort

Fig 4

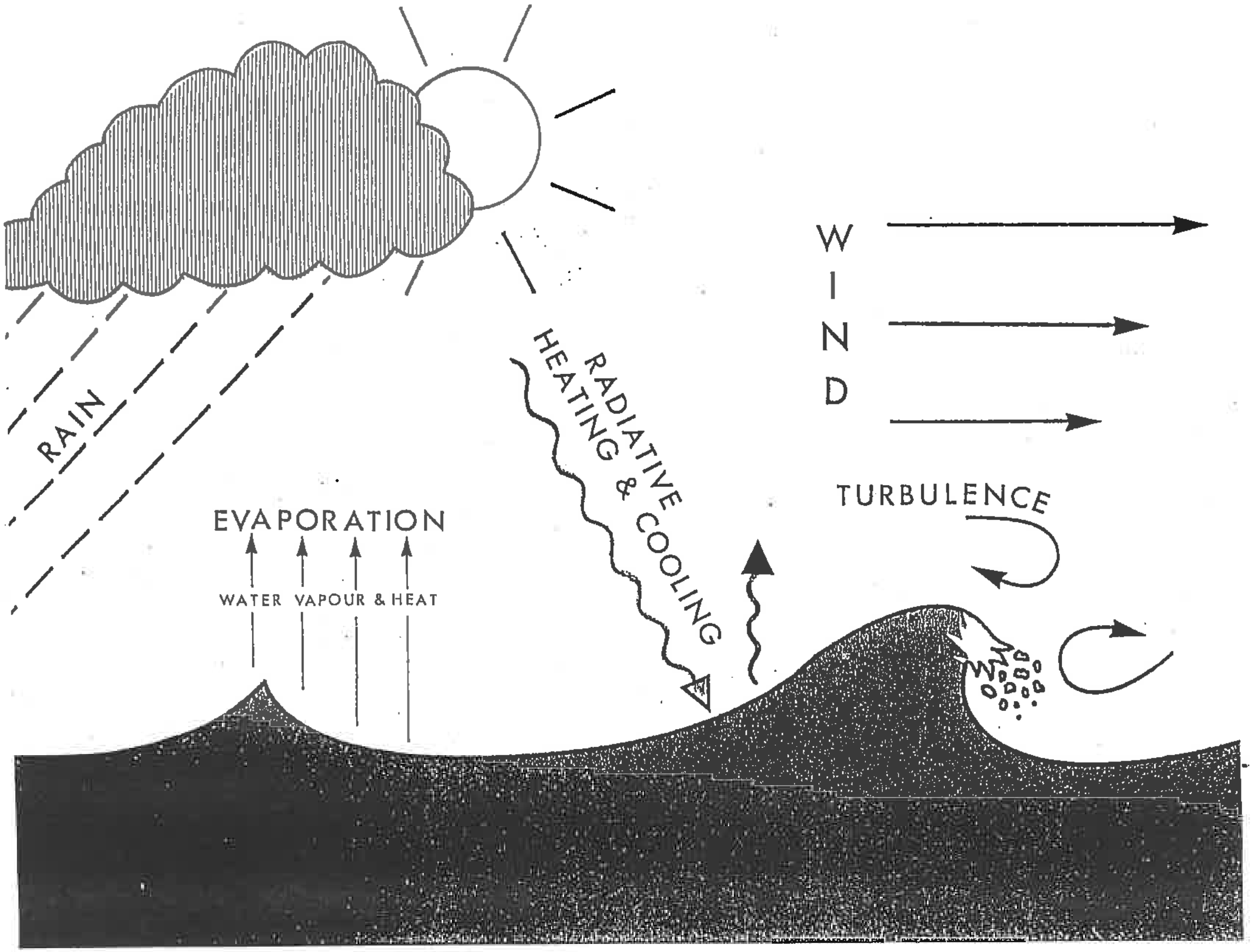

RAIN
EVAPORATION
WATER VAPOUR & HEAT
RADIATIVE
HEATING & COOLING
WIND
TURBULENCE

Fig 5

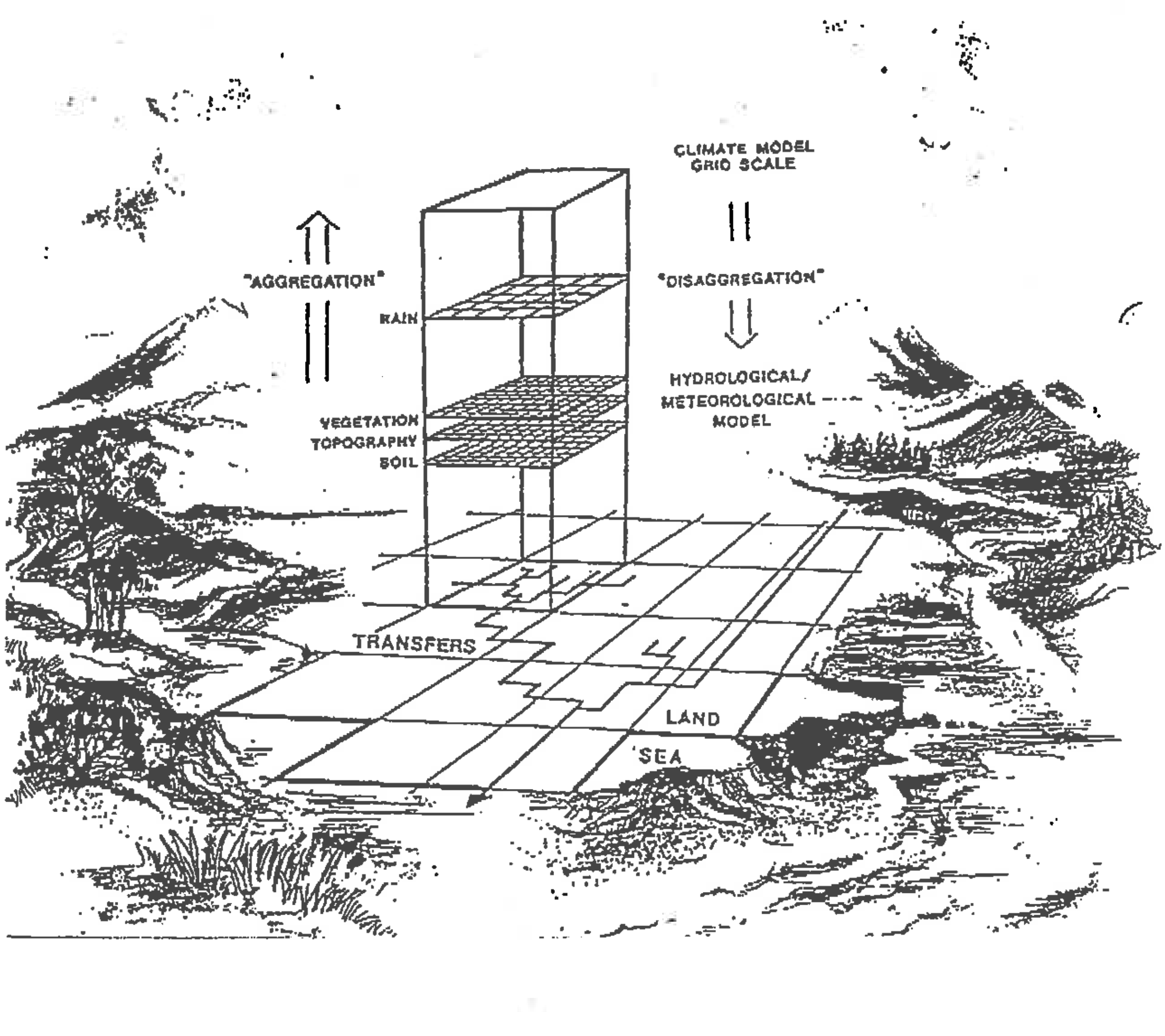

CLIMATE MODEL
GRID SCALE
"AGGREGATION"
"DISAGGREGATION"
RAIN
VEGETATION
TOPOGRAPHY
SOIL
HYDROLOGICAL/
METEOROLOGICAL
MODEL
TRANSFERS
LAND
SEA

Fig 6

CURRENT JCMM INTERNAL REPORTS

This series of JCMM Internal Reports, initiated in 1993, contains unpublished reports and also versions of articles submitted for publication. The complete set of Internal Reports is available from the National Meteorological Library on loan, if required.

1. **Research Strategy and Programme.**
   K A Browning et al
   January 1993

2. **The GEWEX Cloud System Study (GCSS).**
   GEWEX Cloud System Science Team
   January 1993

3. **Evolution of a mesoscale upper tropospheric vorticity maximum and comma cloud from a cloud-free two-dimensional potential vorticity anomaly.**
   K A Browning
   January 1993

4. **The Global Energy and Water Cycle**
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