Physical 3D-Climatology from Hann to the Satellite Era

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I. INTRODUCTION

I am very grateful for the invitation to review the development of physical climatology since the classical contributions of Hann 125 years ago, here in the town where he wrote his most important work. When I was a young student, more than 60 years ago, Hann’s ideas continued to dominate climatology prior to the advent of operational aerology in the 1930’s. I have been fascinated with this field ever since we were on a two-week excursion across the Swiss Alps in the Spring of 1931, where I had to prepare local climatological surveys using the wealth of available data. We realized that the climate changed with altitude, at the coasts and on islands of the lakes, as well as the role of dominant winds and cloud motions in high mountains - only there was a view into the third dimension possible. However, at this time, the fundamentals of the 3D-climatology of our era already existed: a number of regular airplane ascents, and methods to present their results in a physically sound format had been developed [V. Bjerknes, 1910/11; cf. Flohn, 1955]. The crucial role of a 3D-view for a physical understanding of common atmospheric phenomena such as gales and frontal discontinuities had already been formulated by Margules [1905, 1906]. But we young students were unable to imagine that atmospheric sciences, especially climatology, could evolve into a physical science as quickly as they did over the course of the following two decades.

I had been asked to speak on the topic “From Hann to 3D-models”. Since I am not a model specialist, this put me into somewhat of an embarrassing predicament. Consequently, I chose the title, "... to the ERBE-Satellite", expecting access to full results from this highly important instrument - unfortunately only initial evaluations [Ramanathan et al., 1989; Raval and Ramanathan, 1989] are available. So, instead, I prefer a more general title (as above), which indeed refers to the most powerful, accurate and complete information source monitoring the climatic system of our planet from space. Since the title of this Symposium deals with fluxes of matter, I prefer to speak mainly, but not exclusively, on the development of physical climatology with emphasis on one of the most important fluxes: that of water between atmosphere, ocean and soil/vegetation as representing the terrestrial biosphere.

II. HEAT AND WATER BUDGETS AT THE EARTH’S SURFACE

The scientific evolution of climatology around the turn of the century started mainly from the balances of radiation and water at the earth’s surface. Solar radiation was recognized as the...
external source of energy operating within the climate system. Instruments were developed to measure the direct radiation of the sun (S), the diffuse radiation of sky (D), the surface albedo (albedo) and the two components of infrared (long-wave) radiation: the terrestrial radiation up to the sky and the counter-radiation downward from the atmosphere (LW↓ - LW↑). Together with the short-wave radiation balance one obtains the net radiation balance at the surface (Q) on the right side of equation (1): 

\[ Q = Q_{solar} + Q_{infrared} \]

Here, I can omit all historical details since today this equation is well-known in relation to the greenhouse effect, which is included in the term LW↓. I shall only recall a fact which has been too frequently neglected: in a cloud-free atmosphere, about 65% of LW↓ is caused by atmospheric water vapour. The latter designed many instruments, among them one for the measurement of the whole "Strahlungsbilanz" (net radiation), shortwave and longwave together. In the 1930's, progress was rather rapid - F. Linke [1942] gave a comprehensive review on infrared radiation in the Handbook of Geophysics, which appeared unfortunately during World War II. Simultaneously, the turbulent fluxes of sensible and latent heat from the surface into the air were investigated - these are the most important processes with which the earth's surface gets rid of the surplus of energy received by the radiational processes (Q). Relatively small are the conductive heat fluxes into the soil (and to the vegetation: B), first studied by von Bezold [1892] and Homen [1897] in Finland (in cold climates, B also contains the heat necessary for melting the snow-cover, which dominates during the melting period over all other quantities). Of much higher importance are the two turbulent fluxes in the atmosphere [W. Schmidt - Vienna, 1925; "Austausch", H. Lettau, 1939] consisting of sensible heat (H) and the latent heat of water vapour (L*Ev), with \( L = \text{heat of condensation} \), resulting in the heat balance: 

\[ Q = H + L*Ev + B \]
Fig. 1. Diurnal variation of heat budget parameters in the Mongolian Steppe [Albrecht, 1940]. S=net radiation, B=heat flux into soil, L(V) = turbulent fluxes of sensible (latent) heat.

\[ Ev = C_E \rho (q_s - q_a) u \]  

(4)
cannot give more than a first approximation. One has to use time averages for the highly variable parameters \( q_s \), \( q_a \) and (especially) \( u \), and to neglect correlations between them. At the continents, there are two other parameters with episodical or seasonal storage - soil moisture and snow-cover - which are spatially very variable and therefore difficult to handle. One of the most complete early systems of algorithms to solve these problems numerically has been given by Lettau [1969, 1979, 1991].

Lettau [1969] found also a simple relation between three nondimensional parameters, the Bowen ratio \( Bo \), Budyko's dryness ratio \( Bu \) and the runoff factor \( C = RF / P \) used in Hydrology (\( RF = \) runoff, \( P = \) precipitation):

\[ Bu = (1 + Bo)(1 - C) \]  

(5)

In an attempt to improve Thornthwaite's - somewhat oversimplified - methods, Willmott et al. [1985] have given a global review of these parameters and their seasonal variations. Errors in the application of Bowen's method have been discussed by Ohmura [1982].

After Albrecht's return from Australia to a remote village in the Black Forest, still active during his long illness until his death in 1965, A. Baumgartner (Munich) and I then decided to foster a concentrated effort to revise and finalize his work on the main terms of the heat budget for both land and sea. This was to entail a complete evaluation of all available data and as well as a comparison of the results of different algorithms used by Albrecht, Budyko [cf. 1982] and Penman. We received support from the German Research Community, and together with a highly experienced retired climatologist (E. Reichel), Baumgart-

Fig. 2. Seasonal variation of precipitation (land and sea, zonal averages) [Jaeger, 1976].
TABLE 2. Annual water budget (cm/year)

<table>
<thead>
<tr>
<th>Continents</th>
<th>Oceans</th>
<th>Globe</th>
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<tr>
<td></td>
<td>P</td>
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<tr>
<td>Budyko, Korzun</td>
<td>80</td>
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<td>German Authors</td>
<td>78</td>
<td>44</td>
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P = precipitation, E = evaporation, Rf = runoff

ner was able to publish the oceanic part with extended tables and maps in 1975. Somewhat later, Jaeger - on the advice of Kessler - drew the first monthly global maps of precipitation, certainly with much generalization (Fig. 2). Due to the increase of precipitation with height in hardly settled mountains and to the reduction of its measurement caused by wind, the absolute figures are most probably somewhat too low (Table 2). In recent years, marine data have become accessible (COADS, British Meteor. Office, Bunker data) and gratefully welcomed by many scientists. New atlases - on sea surface temperatures and ocean heat gain [Bottomley et al., 1990], North Atlantic Heat Budget [Isemer and Hasse, 1987] - have been published [cf. also Hsiung 1986]. These are the most important sources for comparative investigations at a hemispheric or global scale.

At this time, Henning (then in Bonn) had collected climate records from more than 4000 land stations - compared with about 1600 used by Budyko - and had started, with utmost care, the laborious work of comparative calculations. The drawing of many hundreds of maps for each continent and season was not completed until 1978, but the formulation of the introductory text and the calculation of monthly and annual zonal averages (Figs. 3-4) was increasingly delayed by other commitments and responsibilities of the author. Nevertheless, D. Henning - now working alone - finished the manuscript in 1988, finally to be published in 1989, more than 20 years after its beginning. A future comparison with even more complete results of Willmott and Thornthwaite [Willmott et al., 1985] will be interesting.

Fortunately, Henning's atlas appears to have been published at the right time, when broad-scaled international efforts - the Global Energy and Water Experiment (GEWEX) - aim to improve the basic data on which these fundamental budgets have to be based. Indeed, the evaluation results of the earth's surface energy and water budget are still quite different (Tables 1-2). Bearing in mind the fundamental nature of this data at the time of an apparent beginning of a man-triggered climate fluctuation.

Fig. 3. Seasonal variation of net radiation at the continents (Watt/m²) [Henning, 1989].

Fig. 4. Seasonal variation of evapotranspiration at the continents (Watt/m²) [Henning, 1989].
of possibly far-reaching consequences, one may even speak of a scandalous lack of elemental knowledge in a virtually vital field for mankind as a whole - much more vital than e.g. the research of outer planets.

III. HIGH MOUNTAINS INITIATING 3D-CLIMATOLOGY

During the second half of the 19th century, only the fundamentals of climatology as a physical science had been laid. Hann's greatest merit was the application of thermodynamics within the atmospheric processes - the pure existence of the alpine mountains directed his view (comparable to Alexander von Humboldt) into the third dimension of altitude. His thermodynamic interpretation of Fohn - almost simultaneously with Helmholtz - made him well-known; this principle was essential for all kinds of vertical motions in the atmosphere. Compared with contemporaneous publications, this was a real breakthrough, arriving exactly at the right time. It was his initiative which led to an entire chain of around 10 mountain observatories at levels between 800 and 650 hPa to be set up in Central and Southern Europe since the 1880's. These stations were completely isolated during the winter and reached from the Tatra mountains and the Dinarides to the Appennines and the Pyrenees. He founded the "Oesterreichische Zeitschrift für Meteorologie" [Hann, 1866], which later evolved - after the foundation of the German Meteorological Society (1884) into the "Meteorologische Zeitschrift", a great stimulus of research in Central Europe.

In the 1880's, an important international controversy arose: while in Central Europe, surface anticyclones were warm - which, at first appeared to be contrary to the fundamental hydrostatic equation - American and Russian scientists found their wintertime anticyclones predominantly cold. Only 3-dimensional dynamics could solve the enigma of warm anticyclones, to be interpreted as a 3D-circulation with a large subsiding core.

IV. ATMOSPHERIC CIRCULATION AND 3D-PROCESSES

In Chapter II, the physical processes at the earth's surface have been reviewed, leading to flux balances of radiation, energy and water. But one of the main issues of physical climatology needs 3D-investigations. These are the balances of angular momentum and kinetic energy and their relation to the maintenance of the general circulation of the atmosphere. Today this problem appears to be solved in principle, but the quantitative data are still rather uncertain, even after the advent of the essential satellite wind data not yet evaluated for a climatology.

The first physically correct view of the atmospheric circulation was given as early as 1735 from Hadley (Fig. 5A), while 100 years later Maury developed strange ideas on a crossing of upper-air circulations; his book showed him - seen from today - as a sort of creationist, looking into the bible when his limited physical knowledge found no answer. Then we should remember, that before Ferrel [1856], H. W. Dove [1837, Berlin] outlined the role of eddies (Fig. 5B) in the middle and higher latitudes (but without mathematics). At an advanced age, he lost much of his reputation when he blocked the evolution of synoptic and weather forecasting, and his earlier papers sunk into oblivion. A. Defant [1921] described the atmospheric circulation as a macroturbulence (Grossaustausch), stimulated by the micro-scale approach of W. Schmidt [1917, 1925] here in Vienna. Today our hemispheric maps demonstrate daily the role of waves and vortices in the great wind systems in the sense of the Norwegian school of V. Bjerknes, further developed by C. G. Rossby and his associates. For all details of this historical evolution reference is made to the excellent reviews by E. N. Lorenz [1967, 1991].

Fig. 5. A) atmospheric circulations conceived by Hadley [1735; cf. Lorenz, 1967]. Today, the mean meridional circulation in this form can only prevail above the Tropics; B) atmospheric circulation as conceived by Dove [1837; cf. Lorenz, 1967].
The recent evolution of physical 3D-climatology begins with papers by V. Starr [1948] and E. N. Lorenz [1955], the latter essentially based on Margules [1905]; for details, the reader should refer to Oort [1964]. Quantitative investigations on the maintenance of the general atmospheric circulation could only be based on data from a network of aerological stations, which became available after World War II.

Using such a fairly dense network, one can derive for each quantity to be transported time averages (noted by bars), zonal averages (noted by brackets [ ]), together with deviations from a time average (prime) and deviations from a zonal average (asterisk). At an isobaric surface, the northward transport of a conservative quantity \( K \) (e.g. relative angular momentum, specific humidity, potential temperature) with the meridional wind component \( v \) (positive northward) is then:

\[
[Kv] = [K][v] + (K'v') + (K''v'').
\]  
(6)

Then the sum of all transports consists of three terms on the right side:

a) transport with the mean meridional circulation,
b) transport with the travelling ("transient") eddies,
c) transport with the stationary eddies.

From historical point of view, a) may represent Hadley's cell, b) and c) together Dove-Ferrel's cell.

While J. Bjerknes and his group used geostrophic winds - which could only give first-order approximations, since their meridional component disappears when averaged along a latitude circle - V. Starr and his group used observed winds, which were much less frequent in the first years. With much more data, Starr's approach was repeated by Oort and Peixoto [1983]; here only results for water vapour (Fig. 6) are shown.

It was now possible to calculate (e.g. as a residual) the latitudinal averaged small vertical components and the mean meridional circulations with their unexpectedly large seasonal variations.

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**Fig. 6.** Zonally averaged cross-sections of the northward flux of specific humidity (g/kg•m/sec) [Peixoto and Oort, 1983]: a = sum, b (c) = transport by travelling (stationary) eddies, d = transport by mean meridional circulation; southern latitude values uncertain. Pressure scale in 10 kPa.
Fig. 7. Streamlines of the zonally averaged mean transport of absolute angular momentum (1963-1973) for year (a), December-February (b) and June-August (c). Transitional seasons similar to year, south of Lat. 40°S uncertain, units 10^{16} kg m^2 sec^{-1} [Peixoto and Oort, 1983].

During the year and in the transitional seasons both Hadley cells are nearly symmetric and much stronger than the mid-latitude Ferrel cell or the quite small polar cells. Whereas, during the two extreme seasons, the (meridional) Hadley cell of the winter hemisphere merges with the summer monsoon cell from the other hemisphere and reaches extraordinary intensity in the λ-p plane (cf. equation (6), first term at right). Here the tropical u-component is disregarded. It is much stronger than the v-component, but consists, in the lower troposphere, of two opposing branches: from E at the winter hemisphere, from W at the summer hemisphere. A powerful meridional flow crosses, especially in some longitudes - East coast of Africa, around 110°E - the equator, leading to this strong equatorial cell with (in a latitudinal average) lifting (subsidence) above the summer (winter) hemisphere. It should be noted that during austral summer a weak monsoon system really exists, running from Indonesia across the Indian Ocean to Africa, in spite of quite different topographical conditions. However, such spatial differences can only be demonstrated with sufficient accuracy if one uses the very large number of satellite-borne winds (i.e. cloud motion vectors) which have already greatly improved our knowledge of tropical wind systems and the role of surface topography for their seasonal variations.

At the time of Hann, it was an enigma, what energy may maintain the surface anticyclones with their continuous outflow near the surface. At the Viennese Zentral-Anstalt, M. Margules (1856-1920) found - based on a local network of stations - that the gradients of surface pressure were insufficient to induce the energy of storms. Looking at the low-level temperature gradients, he discovered a more powerful source in what is now described as the mutual conversion between available potential energy APE (he used the term "available kinetic energy") and kinetic energy KE. Evidence for these fundamental processes could only be found after the advent of operational aerology and the discovery of jet-streams ("Freistrahle") [Seilkopf, 1939]. Between 1935 and 1945, we learned about the role of ageostrophic components [Philips, 1939] in the area of the strong baroclinic zones ("frontal zones" of the Norwegian school) and the cross-isobaric mass transports, including the formation of cyclones and anticyclones. In areas with accelerating high-tropospheric winds (i.e. in the entrance region of a jet-stream) this ageostrophic component transports mass to the cold region (with low pressure aloft) north of the jet. In its delta, with decelerating winds, their surplus KE is used for a mass-transport towards the warm side, i.e. against the slope of the isobars (Fig. 8) [Flohn, 1952].
Fig. 8. Schematic view of the jet-stream (Northern Hemisphere, streamlines), the accompanying surface pressure field - note the low level flow (thin arrows, dashed lines) increasing (left) or decreasing (right) the baroclinic flow - and the conversion between APE and KE; thick arrows = cross-isobaric (ageostrophic) mass flow.

Fig. 9. Above: geopotential 20 kPa with geostrophic flow along the isolines, annual average 1967-1988. Below: Surface pressure, annual average, deviations from zonal mean (dashed lines positive, dotted lines negative values, unit 2 hPa); thick arrows = ageostrophic mass flow as in Fig. 8.
A comparison between the average 20 kPa flow and the deviations of surface pressure from the latitudinal mean (Fig. 9) shows, as a composite, the climatological role of these processes. In the region of convergent upper winds APE is converted into KE, and in the region of divergence KE is reconverted into APE. In the lower part of Fig. 9, these anomalies also indicate, in mid-latitudes, areas of most frequent cyclogenesis and anticyclogenesis. Disregarding such a simplified perceptual view, Lorenz [1955, 1967] and other authors derived a system of equations for an evaluation of this energy cycle. Using the most complete set of radiosonde data, Oort and Peixoto [1983] calculated nearly all terms of the balance equations, except generation of potential eddy energy, which had to be estimated.

**DISCUSSION: THE ROLE OF WATER VAPOUR IN CLIMATE AND CLIMATIC CHANGE**

The vital role of water vapour - more exactly: of its latent heat - in 3D-climatic change is as yet not always sufficiently recognized. A parallel evaluation of maritime surface data (COADS) in the Tropics and of near-homogeneous 3D-analyses of the Northern Hemisphere, together with tropical radiosonde and satellite data, led to the result that the effect of "global warming" - most probably triggered by CO$_2$ and other "dry" greenhouse gases - is substantially magnified by the role of water vapour in 3D-circulations [Flohn et al., 1990a, b, 1992]. While the total greenhouse effect adds about 2 Watt/m$^2$ (IPCC-Report) into the atmosphere, ocean warming needed only about 5 percent of it. But its rising energy input into the atmosphere via water vapour is in the order of 12-15 Watt/m$^2$, i.e. an amplification factor of more than 5. An observed increase of tropical water vapour content in the middle troposphere by nearly 30 percent (Fig. 10) [cf. Hense et al., 1988] is accompanied by:

1. an increase of the zonal average evaporation of equatorial oceans (Lat. 10°S-14°N) of nearly 16 percent, equivalent to 15-20 Watt/m$^2$ (Fig. 11); it diminishes poleward of Lat. 30°N, but
2. an increase of precipitation in most land areas, except the subtropical belt Lat. 5°-35°N [Diaz et al., 1989],
3. an intensification of oceanic mid-latitude cyclones [Flohn et al., 1992] along with a rather drastic increase of winter gales above the Pacific and the Atlantic (Fig. 12),
4. a hemispheric (Lat. 20-90°N) increase of surface and tropospheric monthly resultant geostrophic winds in the order of 0.4-0.7 m/s, and
5. an increase of hemispherically averaged meridional and vertical tropospheric temperature gradients by about 5% in 22 years.

These evolutions led, since the 1960's, to a growing intensity of three of the four large-scale, thermally forced circulations: the Hadley cell, the Dove-Ferrel cell and the zonal Walker circulation, while the evidence for the seasonal monsoon cells is not sufficiently conclusive.

How are the observed circulation changes 3) to 5) related to the observed changes of water vapour content? It is well known that ascending motion prevailing in cyclones after condensation leads to rainfall, dependent on available water vapour. Release of more latent heat intensifies vertical ascent, and thus the kinetic and potential energy of the cyclone. Due to the asymmetry of

mid-latitude frontal cyclones, ascending motions are concentrated in its forward section, subsidence in the rear. This favours convergent inflow near the surface and divergent outflow in the upper troposphere, and thus promotes anticyclogenesis on the eastward (outer) side of the cyclone (see the anticyclonic eddies of the trend around the coasts of Spain/Morocco and Oregon) [Flohn et al., 1990a, 1992].

A peculiar evolution is observed in the northern parts of both the Atlantic and the Pacific, within the deepening cyclones north of Lat. 40°N. Here, the strong increase of wind speed causes rising evaporation, and the net radiation during winter is insufficient to heat the oceanic mixing layer - which reaches here very deep as compared with the Tropics. Here Ev rises, with only weak changes of $q_v q_u$, in spite of decreasing $T_d$ [Flohn et al., 1992].

But such evaporative cooling - which is also observed in tropical hurricanes - contributes through latent heat to the small warming of the atmosphere above the polar cap and to the maintenance of its circulation.

The role of the oceans is indeed essential. The warmest tropical oceans - lacking any upwelling of cooler water between Long. 66 and 160°E - warm fastest, heating and moistening the
Evaporation estimated with $v_{\text{wind}}$ - trend:

- 0%
- 50%
- 100%

Fig. 11. Changes of evaporation (linear trend 1949-1989, annual values) at tropical oceans, observed wind speed corrected, different trends (0, 50, 100%). Zonal average Lat. 10°S-14°N, warmest oceans Long. 66°-160°E, upwelling sections E-Pacific south of equator, Long. 85°-120°W.

atmosphere. Upwelling "cool" water along several tropical coasts and equatorial belts is also warming, perhaps due to higher absorption of solar radiation as a result of planctonic algal bloom [Sathyendranath et al., 1991]. The rising frequency of gales (Fig. 12) is also evidenced by a distinct increase - near 30% - of significant wave-heights measured around the British Isles [Bacon and Carter, 1991].

These investigations [Flohn et al., 1992] lead to two important conclusions:

a) the climatic system is now in a state of disequilibrium, with substantially increasing fluxes of energy and water between ocean and atmosphere,

b) the longitudinal and regional variations are so large that latitudinal and global averages cannot give more than a first order approximation.

At present, a large portion of the discussion of the "global warming" is limited to surface temperature, which played a primary role in climatology at the time of Hann and before World War II. But now, after 60 years evolution of physical climatology, this limitation appears to be obsolete, to say the least. We have to deal with climatic processes in three or better yet, four dimensions, with all parameters which have been measured over many decades. The satellite data - I mention especially those observing cloud motions resp. winds and estimating rainfall, or measuring $T_s$ and the main components of the radiation budget (ERBE) - are intended to radically improve our knowledge of the global patterns of the most essential parameters. However, the wealth of data is so great that the evaluation for climatological purposes lags far behind. Looking at the most recent climate changes, it is vital that the facilities for this evaluation be vastly improved, as well as made more accessible to scientists.

Our results, briefly presented here in this Chapter, are inter-
nally coherent. A feedback via water vapor and hydrological cycle, with increasing intensity of atmospheric circulations, of potential and kinetic energy - all this can be observed under our very eyes. These facts can (and must) be cross-checked and verified - only then are they more convincing to skeptics than even the most fascinating (but partly contradicting) model results. We need both: observed facts and model background, to solve our problems.

3D-physical-climatology has greatly helped to understand the spatial and temporal coherency of the ongoing changes of climate. However, the author's task was a look backwards into the recent history of our science; he has to withstand the temptation to speculate about the future - this may be postponed to another opportunity.

Acknowledgement. The untiring assistance of Dr. A. Kapala, Dr. H. R. Knoche (now Garnisch-Partenkirchen) and Dipl. Met. H. Mächel, especially with regard to the figures and the literature, and of Mrs. W. Rubin, with regard to the computer text and language, is greatly appreciated. I am particularly grateful to Proff. M. Hantel for his constructive comments.

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