Water vapour as an amplifier of the greenhouse effect: new aspects

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Summary. In view of the widespread negligence concerning water vapour as the most efficient greenhouse gas, its role in the recent climatic evolution is investigated. Increase of tropospheric water vapour content and rising evaporation (by about 15%) from tropical oceans have been found in recent decades. Evidence for an accelerated hydrologic cycle is given, leading simultaneously to a remarkable intensification of the tropospheric circulation in the Northern Hemisphere. Average geostrophic wind speed at the surface and in the troposphere have increased by 6–9% between 1967 and 1989. This (natural) internal feedback through water vapour amplifies the "dry" greenhouse effect of CO₂ and other trace gases by a factor of about 5, spreading poleward from tropical oceans.

Wasser dampf als ein Verstärker des Treibhaus-Effektes: Neue Aspekte


1. Introduction

In this paper, the authors intend to outline the evidence for a recent intensification of the hydrological cycle and of the tropospheric circulation of the Northern Hemisphere. It is an extension of two recent papers (Flohn et al. 1990a, b), based on marine COADS data for the extended period 1949–1989 and daily hemispheric maps from the German Weather Service between November 1966 and February 1989. The evaluation of this data has also been improved; investigations on the controversial positive trend of surface wind speed at the oceans using geostrophic data are presented in the Appendix.

Recent warnings concerning the expected global warming and climatic change unprecedented since 10⁵ (or 10⁴) years had already been issued by leading U.S. scientists, based mainly on the unconvincing course of global surface temperature (Elsasser 1986, 1990) as well as on the conflicting results of climate models. However, our main arguments are essentially different:

- observed surface data alone are still controversial, in spite of the convincing review of Schönwiese & Stahler (1991). Stronger mid-tropospheric warming and stratospheric cooling are already in progress (Table 1),

<table>
<thead>
<tr>
<th>Pressure (kPa)</th>
<th>Altitude (km)</th>
<th>N Pole (60–90°N)</th>
<th>Tropical (30–30°N)</th>
<th>Equatorial (10–10°N)</th>
<th>S Pole (60–90°S)</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>85–30</td>
<td>1.5–9</td>
<td>+0.16</td>
<td>+0.10</td>
<td>+0.22</td>
<td>+0.40</td>
<td>+0.20</td>
</tr>
<tr>
<td>30–10</td>
<td>9–16</td>
<td>+0.27</td>
<td>-0.32</td>
<td>-0.69</td>
<td>-0.41</td>
<td>-0.46</td>
</tr>
<tr>
<td>10–5</td>
<td>16–20</td>
<td>+0.36</td>
<td>-0.41</td>
<td>-0.99</td>
<td>-0.46</td>
<td>-0.48</td>
</tr>
</tbody>
</table>

- many more parameters are necessary (and data is available) for a conclusive assessment of on-going climatic change,
- climatic models which are not verified with regard to the complete actual surface climate with its seasonal variations and vagaries of weather alone are not sufficiently reliable for recommending far-reaching and expensive strategies to the decision-maker,
- the complete and critical evaluation of all kinds of observations is of the same importance as the critical comparison of comprehensive, truly interacting climate models. Here, only arguments a) and b) shall be discussed in detail; argument c) is shared by many experienced specialists.

In preparation for the second World Climate Conference in Geneva (WCC II, October 1990), the Intergovernmental Panel on Climatic Change (IPCC) issued a comprehensive report "Assessment of Climatic Change" reviewing the physical background and discussing several scenarios for the future fate of the composition of the atmosphere and its effect on climate, together with impacts of climate on human activities and strategies for its mitigation. This report (Houghton et al. 1990) leads the reader to the conclusion that the "scientific community" has reached a consensus on the existence of a man-triggered global warming and on the necessity of far-reaching measures to at least reduce the future emissions of greenhouse gases. In some respect, the reports of the German Parliament's Enquete Commission...
References


"Vorsorge zum Schutz der Erdatmosphäre" (Precautions for the Protection of the Earth’s Atmosphere) — unanimously agreed upon in early November 1990 — are more complete and well balanced (Deutscher Bundestag 1990).

Meanwhile, a vivid discussion arose, particularly in the United States, questioning the role of greenhouse gases and stressing the view that the present global warming did not pass beyond the limits of natural fluctuations as observed during the last 100—150 years (Elsasser 1986, 1990). Unfortunately, this discussion, as well as Section 7 of the IPCC-Report, concentrate primarily on surface temperature and omit many other aspects of the climatic evolution during the last 3—4 decades. In contrast to S. Arrhenius’ classical paper (1896) and in spite of the well-founded estimates of F. Møller (1963) and V. Ramanathan (1981), the leading role of water vapour has widely been neglected, as stressed by K. Kondratyev and others during WCC II. As we shall see, the hydrological cycle, using about 88% of the available net radiation at the ocean’s surface, and clouds play a dominant role in the chain of climatogenetic processes.

Furthermore, climate, within the geophysical science, can only be understood in relation to the 3-dimensional circulation of atmosphere and oceans. Recent evolution of atmospheric 3D-circulation can be followed at the Northern Hemisphere since about 1948. The first marked period of global warming, in the 1920’s and 1930’s, has been described by R. Scherhag (1936a, b, 1939) based on surface maps of temperature and pressure; now we have to look in detail at the entire troposphere and the lower stratosphere.

2. Comments on on-going climatogenetic processes

In addition to the emission of (dry) greenhouse gases, which is the main item of present discussion, several other processes are operating within the climate system. Among them, some comments shall be given to wide-spread changes of land use, in cloudiness, and within the oceanic mixing layer.

1) Changes of land use — mainly in tropical and subtropical continents — lead to higher surface albedo (deforestation, shifting cultivation, over-grazing) and lower soil moisture (soil erosion, biomass burning). These and other examples are consequences of the increasing growth rate of human population, which was also stressed at WCC II.

2) Increasing cloudiness (Henderson-Sellers 1986, 1989) and decreasing sunshine (Weber 1990, Angell 1990) may lead — cf. the important results of the Earth Radiation Budget Satellite (Kalval et al. 1989, Ramanathan 1989) — to a decrease of incoming solar radiation at the surface and thus apparently counteract the greenhouse effect. However, this refers mainly to lower and middle clouds; cold, thin cirrus sheets as diverging from increasing tropical convection (see Chapter 3) or produced by aircraft condensation trails indeed amplify the greenhouse effect.

3) Increasing ocean surface temperature (Flohn & Kapala 1989, Flohn et al. 1990 a, b) causes — with constant or sinking relative humidity and rising wind speed (see Chapters 3, 4 and Appendix) — an exponential rise of evaporation and consequently of the hydrological cycle. In addition to the (radiational) greenhouse effect, this physically different process injects latent heat energy into the atmosphere to be released by precipitation. At many coasts and in marginal seas, increasing inflow of nutrients intensify the production of planktonic algae and the turbidity of surface waters, thus enhance the rate of heating at the ocean’s surface (Sathyendranath et al. 1991).

The examples indicate that man’s role for climate change is much more complicated than that caused by an increase of “greenhouse gases”. The role of biogeochemical processes in the carbon cycle has been reviewed in the IPCC-Report, Section 1.

3. Role of water vapour in on-going climatic change

One of the most essential effects of water vapour occurs during its transport, together with latent heat, from its surface source (evaporation E) to its sink (precipitation P) in the cloud layer of the troposphere. In tropical latitudes, where strong convective clouds reach heights of up to 17 km, the bulk of latent heat is released at altitudes of 2—6 km, in the extratropics mainly at 1—3 km, thus warming the lower and middle troposphere. One millimetre of rainfall (equivalent to 1 liter/m²) releases an energy of 28.6 W/m² (equivalent 57 cal/cm²/day); mean rainfall rates of 4—8 mm/d are normal in the humid tropics. Since the radiational cooling of air is only of the order 0.1 K/h, part of the released latent heat remains within the troposphere for several days. Typical area-averaged rainfall rates in convective cloud clusters and tropical disturbances are 20—30 mm/d; this releases an energy larger than the extraterrestrial solar constant at a rotating earth (340 W/m²). During large-scale disturbances the total area of such cloud clusters can reach 10⁶—10⁷ km².

The average atmospheric residence time of water vapour can be derived from the conventional figures of global precipitation (100 cm/a) and precipitable water of the atmosphere (25 mm) (Peixoto & Oort 1983). Their ratio indicates about 40 recyclings per year and thus an atmospheric residence time of 9 days. Following Peixoto & Oort again (and some of our own local investigations), the speed of vertically integrated transport of water vapour is in the order of 2—2.5 m/sec or about 200 km/d, prevailing in zonal direction. The average distance between source (E) and sink (P) is then in the order of 2000 km, an estimate near the upper limit.

Release of latent heat follows the (relatively small-scale and noisy) rainfall pattern. This differential heating intensifies all types of ascending motion, including baroclinic waves and synoptic-scale cyclones. It should always be remembered that, from the viewpoint of physics, this effect — due to phase changes — is different from the (radiational) greenhouse effect. It is indeed a natural (!) feedback within the climate system, using weak man-induced warming of the ocean’s upper layers for intensifying the atmospheric circulation at local, regional, and hemispheric scales.
The hydrological cycle embraces evaporation (E), precipitation (P), and continental runoff (Rf). Disregarding areas with internal drainage at the arid parts of the continents, the hydrological budget is written:

\[ P_L - E_L - Rf = P_o + Rf - E_o = 0 \]

Continents    Oceans

Here all time-dependent storage terms have been neglected; in the oceans, increasing (decreasing) values of E_o - P_o, i.e. of the fresh-water flux into the air, are indicated by rising (diminishing) salinity (S).

In the Atlantic, data of the trend of salinity (S) between 1955—59 and 1970—74 (LEVITUS 1989) clearly indicate a freshening (i.e. more rainfall) at the belt 0—12 °N, here reinforced by rising Amazon discharge, as well as at the belt 40—60 °N, similar to the positive trend of land data. In equatorial areas, precipitation (P) depends on the height of towering cumulonimbi which penetrate the middle troposphere with its moist-static stability to altitudes up to 17 km, spreading large cirrus sheets outwards. The available latent energy controls the height of cloud tops — the latter can be estimated from satellites measuring outgoing infrared radiation (OLR) decreasing with their temperature. First-order approximations of a conversion between P and OLR are available; these allow only a rough estimate of area-averaged P for areas of the order of 75,000 km². Such data are evaluated e.g. by NITTA & YAMADA (1989), suggesting — if homogeneous — a recent increase of P in the equatorial belt. DIAZ et al. (1989) has also found a significant increase of rainfall for the belt lat. 0—25 °S.

Applying the well-known bulk formula (for discussion see ISEMER & HASSE 1987, 1991), FLOHN & KAPALA (1989) estimated evaporation (E) from the main shipping routes at the belt 10°S—14°N (Fig. 1) for the period 1949—79.

Unfortunately — but typical for our incomplete knowledge of the only planet inhabited by human beings — all these basic figures are hitherto hardly more than educated guesses. Table 2 is primarily derived from HENNING (1989, Table 15), and demonstrates the deplorable gaps in our knowledge of the hydrologic balance, one of the essential parameters for the well-being of the fearfully and rapidly growing human population. After 30 years of expensive space research, geophysical scientists can only hope that the planned Global Energy and Water Budget Experiment (GEWEX) may fill this scandalous gap in a foreseeable future.

At land, the number of available long records of precipitation (P) is rather small, except in the continental belt lat. 35—70 °N, where P has distinctly increased since about 1960 (BRADLEY et al. 1987, DIAZ et al. 1989). In Europe, an increase between 40 and 60 °N has been noted (SCHNEWESE & BIRRONG 1990) since a century or more. In contrast to this, P diminishes in the subtropical belt between 35° and 5 °N extending also to northern Africa, here related to both the Mediterranean winter rains and the tropical summer rains. Tropical rainfall data are hardly sufficiently representative for a reliable zonal analysis; since about 1962, the area-weighted Indian Summer Monsoon rains tend to remain slightly below average (e.g. GREGORY 1989).

Using global rainfall rank statistics from 2° x 2° boxes, the Climatic Diagnostic Center (HALPERT & ROPELEWSKI 1991) has shown a rise of the median rank from 0.44 (1951) to 0.56 (1990), which is statistically significant. Unfortunately, these statistics — well-adapted to the great spatial and temporal variance of precipitation — do not allow a quantitative estimate of the increase of precipitation.

### Table 2. Global water budget estimates after BUDYKO (1978) and German authors (cf. text) in cm water column/year.

<table>
<thead>
<tr>
<th></th>
<th>Continents</th>
<th>Oceans</th>
<th>Globe</th>
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<tbody>
<tr>
<td></td>
<td>P</td>
<td>E</td>
<td>Rf</td>
</tr>
<tr>
<td>BUDYKO, KORZUN</td>
<td>80</td>
<td>45</td>
<td>35</td>
</tr>
<tr>
<td>German authors</td>
<td>78</td>
<td>44</td>
<td>34</td>
</tr>
</tbody>
</table>

P = Precipitation, E = Evaporation, Rf = Runoff.

### Table 3. Variations of sea-air parameters 1949—1989, annual values derived from linear regressions.

<table>
<thead>
<tr>
<th></th>
<th>Atlantic</th>
<th>Warmest oceans</th>
<th>Upwelling Zonal regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_s (°C)</td>
<td>Mean</td>
<td>27.04</td>
<td>28.45</td>
</tr>
<tr>
<td></td>
<td>(Sea surface)</td>
<td>26.94</td>
<td>28.16</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>27.14</td>
<td>28.74</td>
</tr>
<tr>
<td>( \Delta ) in °C</td>
<td>+0.20</td>
<td>+0.58</td>
<td>+0.63</td>
</tr>
<tr>
<td>T_r—T_s (°C)</td>
<td>Mean</td>
<td>0.43</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>(Sea surface)</td>
<td>0.48</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>0.41</td>
<td>0.54</td>
</tr>
<tr>
<td>( \Delta ) in %</td>
<td>-14.6</td>
<td>+38.5</td>
<td>-105.9</td>
</tr>
<tr>
<td>q_e—q (g/kg)</td>
<td>Mean</td>
<td>4.75</td>
<td>5.32</td>
</tr>
<tr>
<td></td>
<td>(Spec. humidity at T_s)</td>
<td>4.69</td>
<td>5.01</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>4.81</td>
<td>5.62</td>
</tr>
<tr>
<td>( \Delta ) in %</td>
<td>+2.6</td>
<td>+12.2</td>
<td>+5.7</td>
</tr>
<tr>
<td>V_{upw} (m/s)</td>
<td>Mean</td>
<td>7.34</td>
<td>6.78</td>
</tr>
<tr>
<td></td>
<td>(estimated)</td>
<td>6.82</td>
<td>6.31</td>
</tr>
<tr>
<td>( \Delta ) in %</td>
<td>+15.7</td>
<td>+14.9</td>
<td>+13.8</td>
</tr>
<tr>
<td>E_{00} (mm/d)</td>
<td>Mean</td>
<td>4.57</td>
<td>4.66</td>
</tr>
<tr>
<td></td>
<td>(estimated)</td>
<td>4.36</td>
<td>4.21</td>
</tr>
<tr>
<td></td>
<td>1989</td>
<td>4.78</td>
<td>5.10</td>
</tr>
<tr>
<td>( \Delta ) in %</td>
<td>+9.6</td>
<td>+21.1</td>
<td>+13.4</td>
</tr>
</tbody>
</table>

1 E is a function of q_e—q, and of corrected wind speed (with 50 % \( V_{upw}=\text{trend} \)).
Fig. 1. Selected COADS 2° × 2° boxes, lat. 10°S—14°N, (black = warmest oceans, dotted = areas with part-time upwelling, all boxes = zonal average).

These data have now been prolonged to 1949-89, with about \(4 \times 10^6\) observations covering nearly \(20 \times 10^6\) km\(^2\). The two variable terms — the saturation deficit \(q_s - q_a\) (\(q = \) specific humidity in g H\(_2\)O/kg air) and the scalar wind speed \(V_{\text{scal}}\) — rose nearly everywhere (Table 3). The positive trend of \(q_s - q_a\) is generally not questioned. It is correlated with a weak, but quite general reduction of relative humidity (RH), which may be due to increasing instability of the marine boundary layer (Fig. 2). The apparent rise of \(V_{\text{scal}}\) is controversial; representative comparisons between \(V_{\text{scal}}\) and geostrophic winds are given in the Appendix. Together with some other results, these independent parameters suggest that the real trend of \(V_{\text{scal}}\) since 1949 can be assumed to be at least 50% of the (biased) observed trend. The largest changes are observed in the warmest oceans with \(T_s > 28^\circ\) (eastern Indian Ocean and western Pacific) (Fig. 3); here \(E\) increased at least by 13% \((V_{\text{scal}}\) assumed to be detrended), at most by 30% (assuming the trend of \(V_{\text{scal}}\) to be real and unbiased). Since the most probable values of \(V_{\text{scal}}\) tend to lie between these extremes, we estimate a value near 21% for the warmest oceans. In the zonal average \((10^\circ S - 14^\circ N)\), the same assumption leads to an increase of \(E\) by 16% \((\pm 8\%\) or about 18 W/m\(^2\), which is surprisingly large and equivalent to a rise from about 142 to 163 cm/s. Representing the zonal average lat. \(10^\circ S - 14^\circ N\) of our data, Fig. 2 gives time series and trends of all important parameters.

This value for \(E\) may serve as a base for a global estimate (Flohn et al. 1990a, b). Baumgartner & Reichel's (1975) data indicate an area-weighted ratio of \(E\) between the global ocean and the belt \(10^\circ S - 15^\circ N\) of 0.74 per unit
of area. Converted into energy units, we reach a global estimate of +13 (±3) W/m². This indicates an additional energy input into the atmosphere from the ocean, i.e. within the climate system, triggered by the warming of the ocean’s surface as a feedback of the “dry” greenhouse effect, but released through a physically different process, i.e. phase changes. This internal feedback is much stronger (RAMANATHAN 1981) than the original (“dry”) greenhouse effect (2 W/m²: IPCC Report 1990). It explains why tropospheric warming (see later) is distinctly stronger than surface warming and why it increases towards the equator, as a mere consequence of the Clausius-Clapeyron equation.

HENSE et al. (1988) have shown that at the 50/70 kPa layer over the equatorial belt, the vertically integrated H₂O-content ("precipitable water"; W) has increased since 1965. Gaffen et al. (1991) essentially confirmed these results in the Tropics and found a regionally different increase of water vapour of up to 50 kPa at many stations in mid-latitudes. On the other hand, Lindzen (1990) made a strong point of a hypothetical drier upper troposphere, without giving evidence. Extending HENSE’s data to the entire layer 30/85 kPa — the changes below 85 kPa are smaller and less striking — Fig. 4 gives a nearly 30% rise of W during 22 years for four stations in Micronesia representing the “warmest oceans”. This is accompanied by a substantial warming of the same layer (30/88 kPa) in the order of about 0.8 K in 22 years, i.e. distinctly more than the global surface average. This strong warming of the tropical troposphere is observed at all stations — even above the southern Indian stations after a change in instrumentation. Table 1 indicates that it does not extend into the higher tropical troposphere — due to its very low H₂O content — and that the entire tropical troposphere between 1.5 and 16 km is destabilized, parallel to an intensification of penetrating convection.

Within the period 1949—79 (Flohn et al. 1990b), the trend of the small difference between sea and air temperature (T_s — T_a) was — outside of areas with upwelling cool water — significantly positive, thus indicating — together with the observed increases in sea surface temperature — a distinct warming of the upper ocean.

**Fig. 3.** Changes of evaporation (linear trend 1949—1989) at tropical oceans, assuming three different values of the observed (biased) V_cal-trend (0, 50, 100%) for different sections (cf. Fig. 1) in mm/d, Watt/m² and % of the 1949 value.

**Abb. 3.** Änderungen der Verdunstung (linearer Trend 1949—1989) über den tropischen Ozeanen unter der Annahme von drei unterschiedlichen Werten des beobachteten V_cal-Trends (0, 50, 100 %) für ausgewählte Gebiete (vgl. Abb. 1) in mm/Tag, Watt/m² und % der Werte von 1949.
with decreasing relative humidity (RH) — that the upper mixing ocean layer warms faster than the air and decreases the stability of the marine boundary layer. This is probably to be interpreted as a consequence of the ocean heat storage, with a time-scale in the order of 20—30 years. During the 1980’s, however, this difference decreased in several areas.

Last not least, the relationship between evaporation and El Niño events in the equatorial eastern Pacific deserves attention. During the cold part of the El Niño cycle, equatorial upwelling transports cool water (at 14—20°C) with high content of nutrients (nitrogen, phosphorus) from the thermocline (at 100—400 m depth) to the surface. In the euphotic zone (above 25 m depth) the growth of planktonic algae (“blooming”) is consequently enforced, and photosynthesis needs much of the CO₂ within the water; in some cases, the CO₂-flux can even be directed from the air into the water. CO₂-flux measurements from research ships and satellite measurements of chlorophyll confirm this hypothesis (WEBER & FLOHN 1984, ELLIOTT et al. 1991); these “cold events” had been accompanied by minima of the CO₂ growth rate in the atmosphere. In “warm events” (El Niño) the nutrient-poor surface water (27—29°C) suppresses the cool water below and releases a maximum of CO₂ into the atmosphere.

A statistical evaluation of sea-air interface parameters in the Galapagos area (lat. 2°S—2°N, long 86—104°W), along the shipping route from Panama to Australia (about

Fig. 6. Linear trends of sea-air parameters (same as Fig. 2, except \( V_{\text{cap}} \) ) along a meridional cross-section (mainly Long 50—20°W, cf. text) in the Atlantic (Lat. 68°N—20°S). \( E_{\text{a}} \) is given as a thick line, \( E_{\text{0}} \) and \( E_{\text{100}} \) — cf. Fig. 3 — thin lines. Note the overall decrease of RH (here not shown, cf. Fig. 2) and the change of sign at 32°N (\( T_{\text{a}} \), \( T_{\text{a}} - T_{\text{e}} \), \( q_{\text{e}} - q_{\text{a}} \), \( E \)).
Consider the vast section between Asia, Africa, and Australia, including the "maritime continent" Indonesia, the monsoon circulation distinguishes itself from the Hadley circulation by the occurrence of seasonally warmer belts on its poleward flanks, away from the cooler (therm) equatorial region, thus causing low-level westerlies together with easterlies in the upper troposphere. In contrast herewith, the meandering high-tropospheric westerlies (Ferrel belt), penetrate in some quasistationary areas diagonally deep into the equatorial region, sometimes even merging from both hemispheres. Situated here are the preferred areas of tropical-extratropical interaction, together with the cloudy surface cols between the subtropical anticyclonic cells.

This short synopsis has been given here, because several comprehending summaries published during the 1970's should be updated on the base of the available satellite observations. Recent observational series shed light onto the occurrence and mechanism of ENSO events and indicate changes in the intensity and/or extension of these circulations. Their investigation needs different observational sources: satellite wind and cloud observations and precipitation data representing dominant vertical motions.

Due to the large gaps in the aerological stations, evidence for a recent intensification of the Hadley cell is only represented by the drop of rainfall in the continental belt 5-35°N, accompanied by the rise of salinity (S) — i.e. the freshwater flux E — P into the atmosphere — over most of the Atlantic between 12 and 35°N (Levitus 1989). Rising precipitation in the ITCZ-belt is suggested by the apparent decrease of OLR from the top of cumulonimbus towers in the period 1974-88 (Nitta & Yamada 1989, Fig. 5). These hints — each alone scarcely significant — are coherent, but need confirmation by verification of the reality of the positive trend of COADS trade winds (see Appendix).

Based on U.S. diagnostic maps of the 70 kPa level, the deviations of the decadal average 1981-90, from a reference period 1951-80, are given by Halpert & Ropelewski (1991, Figs. 41-45) for the year and the four seasons, covering the area 20°N-Pole. Of particular interest is the northern winter (DJF) with a marked intensification of cyclonic cells above both the northern Atlantic and Pacific, together with an intensification of anticyclonic cells centered at Gibraltar and the American West Coast at 55°N. Also, the Siberian High, near Lake Baikal, is strengthened. In all seasons, positive anomalies are significantly rising, while the negative anomalies are relatively small, covering only 20% of the 10°lat./long. intersections between 20 and 70°N.

After World War II, sea-level pressure and 50 kPa analyses became available in the United States in 1946 (Knox et al. 1988, Shabbar et al. 1990, Lamberti 1990), and by the German Weather Service in 1949 (Flohn et al. 1990a, b), the latter without the Pacific section south of lat. 55°N before 1967. Similar diagnostic series certainly exist also in other meteorological centers, such as Moscow and Tokyo, as well as shorter series for the Southern Hemisphere in Melbourne. In all cases, changes of the analysis technique (hand analysis versus objective methods) and of the data...
(new radiosonde stations, temperature and wind data from satellites) leading to inhomogeneities must be taken into account (LAMBERT 1990). Thus our evaluation was first limited to the period 1967—86, now extended until winter 1988/89, also including the levels 85 and 20 kPa.

During the winter half-year, the linear trend of sea-level pressure (Fig. 7) shows a highly significant deepening of both quasistationary cyclones at the northern Atlantic and even stronger in the northern Pacific. This intensification leads, at the forward sections, to strong advection of warm air along with rising pressure at the western coasts of Europe and North America. This is related to the increasing frequency of droughts in the winter-rain areas of the western Mediterranean and of California/Oregon. Using all daily maps (nearly 3,500), the relative frequency of pressure values below 990 hPa had been evaluated. Instead of the linear trend of these frequencies, Fig. 8 indicates the percentage of these values in 1966/67 and 1988/89, derived from this trend. SW of Iceland, this frequency rises from 18 to 27, at the Aleutians, even more, from 17 to 33. This suggests a comparable rise in storminess, which extends, at the Atlantic section, over a very large area from Labrador beyond Novaya Zemlya, covering also the southern coasts of the North Sea and the Baltic Sea. The occurrence of particularly excessive gales during the following winter 1989/90, marks the peak of this trend; in each of the three winter months (DJF), a negative anomaly of 20—25 hPa occurred in the Icelandic area.

This is accompanied by a significant annual warming of the lower troposphere, reaching about 1°C/20a (zonal average) in the Tropics and Subtropics up to lat. 40°N, then decreasing northward to values close to 0°C near the pole (Fig. 9). This warming is distinctly higher above the continents, while above parts of the high-latitude ocean rather small areas with cooling are observed. This leads to an intensification of zonal tropospheric winds and of baroclinicity in mid-latitudes. The annual warming trend of the extratropical lower troposphere (lat. 20—90°N, except the surface layer 85/100 kPa) reaches about 0.7 K (virtual) in 22 years (Fig. 10). This warming also depends, for a zonal belt lat. 45—70°N, on longitude, with highest values above the Rockies and the Ural Mts.

All these observed facts (Flohn et al. 1990a, b) coincide to an unexpected but distinct intensification of the extratropical (Ferrel) circulation. Fig. 11 demonstrates, at 20 kPa, marked longitudinal differences of the recent evolution.

Fig. 7. Surface pressure (October—March), average and linear trend for 1966/7—1988/9 in hPa. Note the significant pressure rise in the Azores High and above West-Central Europe.

Fig. 8. Relative frequency (%) of sea-level pressure below 990 hPa, for November—March 1966/7 and 1988/9, derived from linear trends (see text).


Fig. 9. Meridional section of the virtual temperature trend (thickness) of the 50/85 kPa layer 1967—1988, Year (solid line), November—April (dashed line) and May—October (dotted line); see also Fig. 10 (above).

Abb. 9. Meridionaler Schnitt für den Trend der virtuellen Temperatur (Schichtdicke) der Schicht 50/85 kPa 1967—1988, Jahreswerte (durchgezogene Linie), November—April (gestrichelte Linie) und Mai—Oktober (gepunktete Linie); siehe auch Abb. 10 (oben).

Fig. 10. Above: time series of annual averages of virtual temperature (thickness) of the 50/85 kPa layer, 1967—1988, hemispheric averages lat. 20°N-Pole. Below: linear trend of the 50/100 kPa layer averaged over the zonal belt lat. 45—70°N as a function of longitude between 1967 (solid line) and 1988 (dotted line). Note the shift of the cold troughs towards the east.

Fig. 11. Average annual geostrophic wind speed at 20 kPa and its linear trend 1967–1988. Note the three centers above Japan, the Gulf Stream region, and the SE coasts of the Mediterranean. Note the southward displacement of the East Asian center, in contrast to the northward shift of the others, and the weakening of the Mediterranean center.

averaged over the year. The strong cyclonic intensification over the Pacific leads to a southward shift and intensification of the East Asian Jet, which extends towards the east. The Gulf Stream Jet also extends towards ENE, while the weakening Mediterranean Jet shifts towards the north, caused by the anticyclonic development over western and southern Europe.

The 50 kPa level represents the middle troposphere between 3 and 7 km altitude quite well. Fig. 12 shows the annual average geostrophic flow at this level, indicating two broad quasistationary troughs over eastern Siberia and easternmost Canada and the baroclinic center of the westerlies in latitudes 35°–45°N (Pacific) and 45°–55°N (Atlantic). The trend of annual flow is governed by a marked cyclone above the Aleutian Low and a weaker one centered SW of Iceland. Anticyclonic flow trends are indicated above the Alps and in the Canadian Rockies. Fig. 13 demonstrates the seasonal differences in this trend of tropospheric flow: during summer, marked anticyclonic eddies above the western Mediterranean, the mid-western U.S., the eastern Pacific (l), northwestern Siberia and — remarkable strong — above the Himalayas. Cyclonic eddies are developed above Scandinavia, the Chukchi Peninsula, (weakly) above Central Asia, and (somewhat uncertain) above Morocco. During winter, giant cyclonic cells centered south of Greenland and the Aleutians are superposed to the time-averaged flow, together with anticyclonic eddies near Lake Baikal, the Canadian Rockies, and west of Gibraltar. The intensification of the tropospheric circulation above the oceans is distinctly stronger in winter than in summer — probably correlated with the seasonal variation of mid-latitude evaporation, indicating a strong feedback between hydrological cycle and cyclogenesis. This intensification is also stronger above the Pacific than above the Atlantic — perhaps as a response to the most powerful H2O source at the warmest waters of the western Pacific.

Data for the monsoon circulation are hardly sufficiently reliable for a trend analysis. Unfortunately, some aerological series above tropical Africa and India show serious inhomogeneities and errors within several parameters, even
upper winds, which prejudice a numerically trustworthy month-to-month analysis. Assuming that their bias remains constant during the year, the trend of surface winds varies seasonally; available data suggest a relative weakening during summer and an intensification during winter.

The main branch of the Walker circulation extends between the strongest heating center (Indonesia and West Pacific) and the upwelling region along the west coast of South America and the Galapagos. Here, as well as along other coastal regions with seasonal upwelling of cold water, a slight drop of sea surface temperature (until 1979) and the trends of other parameters at the sea-air interface (cf. Table 3) indicate a general increase of upwelling (BAKUN 1990), which, at the same time, is a convincing argument for higher wind speed. Together with the greatest warming of the western Pacific, this indicates a strengthening of the Walker circulation.

A 3D-evaluation of the monthly averaged maps also allows an estimate of the time variations of meridional temperature gradients (in K/1000 km) and vertical lapse rates (in K/km) for the hemispheric 50/100 kPa layer (lat. 20°N-Pole). The results do not vary substantially with season. They indicate — over 66% of the total hemisphere

— an increase of the meridional gradient and of the lapse rate each by about 4% in 22 years. These values may serve as quantitative measures for the intensification of the 3D-circulation of the Northern Hemisphere.

Since our diagnostic data are available for the entire hemisphere since 1966/7, we omitted the analyses for the whole polar region, for the Atlantic and adjacent continents since 1949, in this chapter. These series indicate a warmer period in the 1950’s and an abrupt change around 1962 (cf. KNOX et al. 1988) to a cooler mode. Exactly at this time, data series from East Africa (FLOHN 1987) and the Indian Ocean (REVERDIN et al. 1986), along with subsurface ocean data from the Labrador and Greenland Sea, suggested a much larger extension of this event, and shall be investigated at a later date.

5. Conclusions

Some of the essential results of our purely empirical investigation of the recent climatic evolution can be summarized as follows:
Fig. 13. Linear trends of the geostrophic flow patterns at the 50 kPa-level, for two seasons: (above) November—March 1966/7—1988/9, (below) May—September 1967-1988. Note the shift of the cyclonic trend patterns from winter towards summer above the Pacific (towards NNW) and the Atlantic (towards ENE); see text also.

1) In tropical oceans, a distinct increase of $T$, since 1949 is in the order of 0.01 K/a. Assuming a mixed layer of 100 m depth, this warming needs only 0.13 W/m$^2$, thus about 5% of the "dry" greenhouse effect of CO$_2$ and other trace gases.

2) Due to the heat storage capacity of the ocean, this small warming leads, 20—30 years later, to a substantial increase of evaporation of up to 15% and of the H$_2$O content of the global atmosphere. It releases latent heat via clouds and precipitation with ascending motion and consequently causes increasing tropospheric cyclonic circulation and winds, notably above the oceans.

3) In middle and higher latitudes, the real increase of surface wind speed — in the order of 8—10% — at the ocean surface leads to cooling by evaporation; there, this process seems to counteract the radiational warming by the greenhouse effect and to maintain, to some extent, the cold polar vortex with its particular circulation.

4) Increasing cyclonic activity at mid-latitude oceans leads, at the forward flank of the cyclones above the western coasts of continents, to the formation of anticyclonic ridges with warm air advection and subsiding motions, i.e. more frequent droughts, notably during the cool season.

5) The intensification of the hydrologic cycle injects, after a delay of some decades, an additional energy in the order of 12—15 W/m$^2$ from the ocean to the atmosphere. This natural (internal) process is due to phase changes of water vapour, but triggered as amplifying feedback by the (radiational) anthropogenic greenhouse effect.

6) This evolution explains why the warming of the troposphere is larger at the level of low and middle clouds than at the surface and is higher in the Tropics than in the polar latitudes. These changes — disregarding here all regional and local peculiarities as well as the seasonal and interannual variability of the trends — are mainly produced by water vapour as an amplifier of the "dry" greenhouse effect of CO$_2$, CH$_4$, N$_2$O and the CFM's. This certainly explains much of the anomalies which apparently contradict the greenhouse effect on global warming. Indeed, the (positive) feedback mechanisms operating via water vapour, clouds, and precip-
itation are — as indicated by HANSEN, SCHLEISINGER, and others (see IPCC-Report, Section 3) — much more effective than the snow-ice-albedo feedback.

This explains the dominance of warming in the Tropics over the polar latitudes — in addition to the simple geographical fact that the tropical oceans alone, between lat. 20°N and 20°S, cover nearly 133 x 10^6 km^2, in contrast to the area of both polar caps between lat. 70° and the Pole with only 31 x 10^6 km^2 together.

6. Comments (H.F.)

It is difficult to understand why this dominant feedback by water vapour and its phase changes has been nearly completely neglected (a case of infectious amnesia?), in spite of the convincing estimates by F. MOLLER (1963) and V. RAMANATHAN (1981). There is nothing new or unexpected about this role — one can find it in most textbooks and monographs which line the bookshelves of every physically-oriented climatologist.

On the other hand, we should withstand the temptation to simply extrapolate the present evolution — this is certainly no adequate solution. If the warming of the oceans and the intensification of their wind-driven circulation proceeds — as one should expect for the next decades — the probability of a rapid retreat of the Arctic sea-ice should rise, even to its total (at least seasonal) disappearance. This may ultimately lead us, in the near future, into an amazing pattern of unipolar glaciation which controlled the earth’s climate during the late Miocene/early Pliocene, between about 14 and 3.3 million years ago (FLOHN 1979, BUDYKO 1991: see IPCC-Report p. 203). “What has happened, may happen again”; for further discussion see RUDDIMAN & KUTZBACH (1989).

In this paper, the fascinating but at least regionally conflicting conclusions from many climate models have hardly been mentioned — we may refer instead to the IPCC-Report (Sections 1—6). However, it should also be noted with satisfaction that at present, the most recent results with a coupled, interactive ocean-atmosphere model — developed at the Max-Planck Institute in Hamburg — show, in its first decades, improved correspondence with the evolution of conventional observations. This growing coherence between facts and models is most welcome (with a sigh of relief!) — its final appearance may be based mainly on a more realistic parameterization of sub-grid-scale effects, such as penetrating tropical convection and the broken pattern of polar sea-ice with its leads and polynyas.

In contrast to such a growing consensus, a working group planning to update the (mostly highly valuable) IPCC-Report had only found “intentionally limited” space for observations. Are we still living in the scholastic era of the 13th century?

Regarding the reluctance of responsible decision-makers to accept — lacking convincing facts — the conflicting results of the majority of climate models as a base for expensive (and unpopular) preventive measures, there is no reason for the community of model-designers to stay in their illuminated ivory tower. Indeed, more research is needed for improved, rigidly verified (!) models as well as for critical and complete (!) evaluations of all data sources, conventional or with sophisticated technology.

But, do we really have sufficient time for this research? The answer should be: No — with the inclusion of water vapour as an overwhelmingly powerful natural agent, available everywhere, processes leading to drastic and rather rapid climatic changes are already in full swing. They will ultimately lead to all kinds of extreme weather events beyond our imagination. We have to live with them while trying our best to decelerate their progress and to mitigate their impact, notably on the precarious water budget. Strategies towards that goal have been elaborated, but immense common efforts are desperately needed.

Acknowledgments

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Appendix: How realistic is the global rise of wind speed?

One of the basic questions in our research was the reality and magnitude of the rising wind speed as suggested by the maritime COADS data. According to RAMAGE (1987), this rise could be an artifact caused by the slow transition from subjective estimates based on the state of seaways to measurements. Since this paper, many local contributions with conflicting results have been presented, which cannot, at this time, be discussed nor quoted in detail. In this context, however, some comparisons between observed and geostrophic winds (the latter based on pressure data from the COADS series) shall be given, along with some area-averaged estimates based on the daily hemispheric synoptic maps from the German Weather Service (see Chapter 4).

The most promising area for a representative verification is the tropical Atlantic, where the available data are much more plentiful than at other tropical oceans. We selected the belt lat. 14—26°N, long. 20—50°W, since the center of the trade wind belt is found at this latitude during the entire year. The data coverage is optimal — the number of 2° x 2° boxes with less than 5 observations per month is marginal. Since the average resultant wind blows from 67° (ENE), we can limit the comparison to the zonal component (U). Fig. 14 shows the annual values (1949—1989) for the observed (above) and geostrophic U-component; the apparently downward linear trend represents in fact rising values due to the negative sign of the easterlies. Since the observed COADS-values are uncorrected — using an obsolete conversion table (ISEMER & HASSE 1987) — an (absolute) correction of +2 m/s or at least of +1.4 m/s (FLOHN et al. 1990a) should be applied. The real observed easterlies should increase from about 6 to 7 m/s, thus reaching about 85% of the geostrophic easterly component.
The linear trend of the observed U-components is $-0.773 \text{ m/s}$ in 41 years; that of the geostrophic U-component ($-0.778 \text{ m/s}$) is practically identical. The correlation between annual values and linear trend is -0.59 for the observed winds, -0.37 for the geostrophic winds (with a greater variance), significant at the 99.9 % resp. 95 % level. A comparison of the individual years indicates a coincidence of very high (1973) and very low (1968) values. This result suggests that our assumption that only 50 % of the trend is real is too conservative.

From the monthly resultant geostrophic winds, which can be calculated from German weather maps for each 5° (lat) $\times 10^5$ (long.) box, one can derive monthly and annual weighted hemispheric averages for the latitudes 20°-$90^\circ$N. Time series have been prepared, together with a linear trend, for the 22a-period 1967-1988, for sea-level pressure, 85, 50, and 20 kPa levels. As an example, Fig. 15 shows data from the 50 kPa level for the year (above) and the extreme seasons (middle and bottom); the significance of the trends are above 95 %. Averages and trends increase sharply from summer to winter. Table A1 gives averages and trends; they indicate that in the troposphere the linear trends are nearly equal or higher than those at the surface.

This apparent rise of tropospheric geostrophic winds coincides well with the similarly derived value of the horizontal gradient of the virtual temperature of the 50/100 kPa layer. Here the average gradient of 5.3 K/100 km increases during the 22a-period by +0.24°C or 4.5 %.

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Referate

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höhen für die Bundesrepublik Deutschland. — Selbstverlag Deut­sches Wetterdienst, Offenbach am Main, 1990. 13 S., 40 Karten
1980. Nur zusammen lieferbar, DM 349,—.

Als ein Ergebnis des Projektes KOSTRA wird mit der Untersu­chung über Starkniederschlags­höhen ein zwischen Meteorologen
und Hydrologen abgestimmtes einheitliches Niederschlagsregel­
werk vorgelegt.

Der Teil 1 behandelt die Flächenverteilung der Niederschlags­
höhen der Langzeitniederschläge von 24, 48 und 72 Stunden für
Wiederhöhungszeit­spannen von 1, 10 und 100 Jahren der Som­mermonate (Mai bis September), der Wintermonate (Oktober bis
April) und dem Jahr (Januar bis Dezember). Ergänzt werden diese
Karten durch ein Tabellenwerk mit Einzelauswertungen von 1065 ausgewählten Stationen, sowie einem Stationslexikon, einem er­
lautierten Text und Interpretationshilfen.

Der Teil 2 enthält für die Sommermonate die Flächenverteilung der Niederschlags­höhen für die Wiederkehrzeiten 1, 10 und 100
Jahre der Dauerstufe 12 Monate sowie für die Wiederkehrzeiten 1,
2, 5, 10 und 100 Jahre die Dauerstufe 15 und 60 Minuten. Ergänzt
wird die Karten durch Einzelauswertung von 125 Stationen.

Das übersichtlich aufgebaute Werk erfordert nur eine kurze Ein­arbeitung für den praktischen Gebrauch. Es ermöglicht
mühelos die Berechnung der Starkniederschlags­höhen bei vorge­
gebener Dauer und Wiederkehrzeit oder die Bestimmung der Wie­derkehrzeiten, wenn die beiden anderen Größen vorgegeben sind. Es
ist für viele Bemessungsaufgaben in der Wasserwirtschaft eine un­ersetzbare Grundlage. Das Kartenwerk ist eine gelungene Neube­
arbeitung und Erweiterung der 1940 von Reinhold herausgegebenen
Publikation über Starkregen in Deutschland. Da die Karten nur die
alten Bundesländer umfassen, wäre eine Erweiterung auf die neuen
Bundesländer dringend erwünscht. U. Maniak, Braunschweig


Die Autoren beschreiben als Ziel ihres Buches zum einen die
Darstellung der physikalischen und chemischen Eigenschaften der
atmosphärischen Aerosoleilchen und -kerne und zum anderen in
einer kohärenten Form ihre Rolle bei der Bildung von Wolken
und Niederschlag sowie beim Klima. In einem klein und ansprech­
end gehaltenen Buch sollen Studenten und Anfänger angespro­chen, aber auch aktive Wissenschaftler durch die Literaturüber­
sicht interessiert werden. In vier Kapiteln werden die folgenden
Themenkreise angesprochen: Das atmosphärische Aerosol, Wol­
kenkondensationskerne, Eiskeime, Aerosol und Klima. In Anhän­
gen wird näher eingegangen auf: Grundlegende Konzepte der
Reinhaltung, Wachstum von Wolkentropfen, Strahlungs­transfer,
Terminologie. Die einzelnen Kapitel sind von verschiedenen Auto­
ren geschrieben.

Die Zusammenstellung der behandelten Themen war dringend
notwendig. Würden sie doch in der Vergangenheit versteckt in
anderen Büchern behandelt (Twomey, 1977: Atmospheric Aeros­
sols; Pruppacher and Klett, 1978: Microphysics of Clouds and Precipitation; Warneck, 1988: Chemistry of the Natural Atmos­
phere). Dadurch wird nun ein recht breiter Überblick möglich
und Anfänger sollten prinzipiell die Chance eines Überblickes
erhalten. Die Autoren sind bestens in den jeweiligen Arbeitsgebe­
ten ausgewiesen und präsentieren die Informationen in einer soli­
den, ausgewogenen und pädagogischen Weise. Die Verwendung
evergleichungen unterstreicht den physikalischen und chemischen
Verständnis­auftrag und verleitet sich nicht in der unsinnigen An­
häu­fung von empirischen Gleichungen, deren Lebenszeit nur bis
zur nächsten Veröffentlichung reicht. Hervorzuheben sind die

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