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The Mobile Polar High: a new concept explaining present mechanisms of meridional air-mass and energy exchanges and global propagation of palaeoclimatic changes

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ABSTRACT

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Air-mass and energy transportation is chiefly made by large lenses of cold air, the Mobile Polar Highs, the key factor of meridional air exchanges, which organize migratory units of circulation in troposphere low levels Mobile Polar Highs (MPHs) originate in the downwards airmotion in high latitudes The cold air injection organizes a dipolar vortex of very large size (2000/3000 km), the anticyclonic side of this vortex (precisely the MPH) is thin, about 1 5 km thick, by reason of cold air density Mobile Polar Highs migrate roughly eastwards, with a meridional component towards the tropical zone, through the middle latitudes where they are responsible for weather variability and for rain-making conditions Their own thermo-dynamic evolution and relief divide them into fragments, and they supply the low-layer of the trade circulation, and eventually the monsoon (previously trade) circulation of a cross-equatorial drift Eastwards movement and disposition of relief govern the MPHs paths and determine distinct aerological domains, in one of these domains, China is precisely located at the eastern Asian exit of MPHs, stopped by the Himalaya/Tibet range, on their southern side during their eastwards migration Power of the MPH, connected with its density, as observed in winter in the present conditions, is a function of the initial temperature, namely of the polar radiative conditions It is precisely in the high latitudes that radiation balance and temperature changes are the most important, at all scales of time, from the seasonal to the palaeoclimatic scale, while in tropical latitudes the changes are comparatively always weak Two modes of troposphere general circulation are a result of this mechanism (1) A rapid mode of circulation, connected with a cold situation in polar latitudes, is characterized by strong and extended MPHs and strong winds at all latitudes and all levels (2) A slow mode of circulation, connected with a warm situation in polar latitudes, is characterized by weak and less extended MPHs, and weak winds at all latitudes and all levels Insolation and surface boundary conditions of high latitudes are the key control of MPHs dynamics, and therefore the key control of palaeoclimatic changes

Introduction

Components of general circulation of the atmosphere, and connected meridional exchanges, are generally considered on the scale of averages. Pressure action centers "statistically" defined are thought to be "permanent"; such is the case, for example, of the "Icelandic Low" and "Azores High" in the northern Atlantic Ocean (Johannessen, 1970, Manley, 1970). Climatic changes are then considered as a result of the modification of either action center and for example of pressure gradient variation between highs (the "subtropical high pressure centers") and lows ("polar or subpolar lows"). Meridional exchanges are also thought to be acted by linear airstreams (winds), included in separate circulations as the Hadley, Ferrel or Walker cells

Climatic changes are then connected with variations of these actions centers, in power, or in latitudinal position. For example, the COHMAP members (1988) considered that in the Pacific

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Ocean at 18 ka the "Aleutian low" was "stronger", while the "subtropical high" (of "Hawaï") was "weaker", but the latter was on the contrary "stronger" at 9 ka and 6 ka.

This point of view corresponds in fact to a "statistical" vision of meteorological phenomena Action centers have been defined on pressure and wind averages, but the question is not asked, to know what the resulting mean initially has been made from, or of what real repetitive phenomena the mean is a result For example, what is the real cause of a "subtropical high", for what reason is it "stronger" or "weaker", and does a relationship as "weak low/strong high" (COHMAP, 1988) fit the real dynamics? Are such relations real explanations, insofar as they only postpone the response for one degree, while the actual initial causes remain still undetermined?

It is obvious that the notion of "permanence" relative to action centers represents only a convenience for discussion, because in the meteorological reality nothing is "stable", everything is always moving. To analyse the actual dynamics of climate, and particularly the actual processes of circulation, one must take into account that meridional air and energy exchanges are chiefly made under the form of large migratory airmasses. It appears, therefore, necessary to integrate the meteorological phenomena in a comprehensive view at the largest scale, the one of the troposphere circulation and to determine how the general circulation is governed by the "pacemaker of the ice ages", the varying insolation reaching the earth surface.

Weather analysis of middle latitudes: evolution of the concepts

The synoptic meteorology of polar and middle latitudes is still chiefly founded on the concepts of the so-called "Norwegian" school of thought (Bjerknes and Solberg, 1921, 1922) The basic model had been undoubtly remarkable in its time, taking into account the contemporaneous observational technology and network, and it had progressively became as a "dogma". However, it was at that time only able to give a partial view of the meteorological reality, both vertically and horizontally, stressing the low levels of the troposphere (at that time quasi-solely observed) and a limited geographical area where mainly appears the "Icelandic low". The "Norwegian disturbance" had consequently highlighted the low character, the "cyclone", but did not clearly explained it, because it was not then possible to fit the low into its right place, in a comprehensive pattern from which it represents only a little part, as now clearly highlighted by the satellite imagery

The depression, or "extratropical cyclone" or "polar low", considered as the key factor of weather, has been by turn considered, since 1880, of "thermal" origin, and then of frontal, next requiring an upper level divergence or a baroclinic instability Thus, the synoptic analysis moved off surface phenomena to upper air data (Uccellini, 1988). The increasing upper-air observations had allowed the kinematical school of thought to give priority to the troposhere upper levels. Analysis of the low levels had then been completed (Bjerknes, 1937; Bjerknes and Palmen, 1937), and progressively their influence had been thrown away on behalf of "altitude". Concurrently the "planetary wave" theory expressed by the "Rossby waves" (1939), undulations of the westerly jet-stream, became "the basic phenomenon of the general circulation of the atmosphere in temperate regions" (Wallen, 1970), since then considered as "one key feature of the mid-latitudes climates" (COHMAP, 1988)

Several further studies completed these concepts (cf. Namias, 1983, Nexton, 1988; Reed, 1988), from the "instable baroclinic waves" in the westerly flow (Charney, 1947, Reed, 1979), to the thermal convection hypothesis and chiefly to the theory of the "Conditional Instability of Second Kind, CISK" (Charney and Eliassen, 1964), transposed from the tropical zone to the mid-latitudes by Rasmussen (1979). In spite of these complements, the real connection between "jet and front" remains approximate, and does not clearly demonstrate the direction of the relationship between different atmospheric levels. For example, is the upper jet-stream the cause or the consequence of the low levels phenomena?

Let us consider only one example The irregu-

lar variations in the position and intensity of the westerly jet are believed to be the cause of variations in surface weather conditions, in spite of the very considerable differences of air density between the high and low levels, and despite the strong temperature modifications induced by vertical air-motions . Consequently, it seems difficult to explain the climatic changes by variations in the amplitude of the "planetary wave" Particularly because a major ambiguity already appears in the explanation of meridional exchanges, at the seasonal scale, during an "index cycle" A "low index" concerns summer (= slow westerly jet and large undulations), but a "high index" concerns winter (= rapid westerly jet and weak undulations). Actual observation shows that the jet is undoubtly more rapid and regular in winter, the seasonal period of reinforced exchanges If it is supposed that large undulations are necessary to intensify meridional exchanges, what physical process can clearly explain that low levels cold air outbreaks are stronger and more numerous in winter?

In short, there is not yet an unanimity on the genesis of lows. Theories emphasize the intensification of an initial low, but "they do not really explain the actual cyclogenesis process, namely the formation of the initial low" (Thépenier, 1983).

There is therefore no synthetic concept and no comprehensive model, because at the synoptic scale the causal relation with the connected anticyclone is not yet established. As a result, at the statistical scale, the actual dynamical relation between a so-called "subtropical high" and a "subpolar low" is not yet clearly determined Usually, only the cyclones are studied, for example in the northern Pacific, where the "extratropical cyclones tracks" were examined by Gyakum et al. (1988), Anderson et al (1989), or Yarnal et al. (1989) who determined the "climatology of polar lows cyclogenetic regions"

However, at the synoptic scale, anticyclones have been observed for a long time. Post-cyclonic or post-frontal cold or polar outbreaks, were only considered as simple consequences, chiefly from upper levels phenomena, and particularly as a result of "the cold advection in the layer 1000-500 hpa on the western side of the surface low" (Palmen et al., 1969)

In surface (and low levels), migratory anticyclones have been observed in the southern hemisphere, and thus they were considered as a specific austral phenomenon. For example, Duvergé (1949) has emphasized the "unceasing circulation" of anticyclones in the southwestern Indian Ocean, Zhdanov (1967) has observed the anticyclones and cyclones paths around Antarctic, and Ratisbona (1976) has noticed the northwards motion, up to the Amazon margin, of "cold airmasses of polar origin reflected in the isobaric field by cold anticyclones". In Australia mobile highs also were described, but Gentilli (1971) thought that "the descending air which causes the belt of high pressure and tropical divergence is subdivided, as a result of the Coriolis effect, into a series of travelling anticyclones".

Klein (1957) has observed the "principal tracks of cyclones and anticyclones" in the whole northern hemisphere In the North American and Atlantic area the unceasant procession cyclone/anticyclone has been observed for a long time, for example by Pettersen (1956), Reitan (1974) and Colucci (1976). But it has been generally considered that "anticyclones tend to dissipate along the eastern coast of the United States" (Zishka et al., 1980), or that the "development of shallow atmospheric fronts above sea-surface temperature gradients" along the American eastern side is dependent on a "coastal air-sea interaction" (Bane et al., 1990; Nielsen et al , 1990). The same concept is applied to the northwestern Pacific area where "the land-sea configuration, the topography of the land masses . , the location of warm and cold currents, the seasonal cycle of the ocean atmosphere–cryosphere system" were estimated to be "responsible for this mean distribution" of lows (Yarnal et al., 1989). Even in the tropical regions, in the prolongation of mid-latitudes phenomena, as noticed by Atkinson (1971), the existence of low-troposphere anticyclones "has been known for many years", but once again "little was understood, however, about the development and movement of these anticyclones".

Nevertheless, very outspread anticyclonic masses are unceasingly streaming on the synoptic

maps, and the satellite imagery clearly shows the displacement of their connected cloud pattern The key contribution of satellite pictures reveals that the cloud organisation is rarely consistent with the classical schemes, in a surprising ratio of "1 for 50". This conclusion highlights the "insufficiencies of the different concepts", and certainly explains why "the meteorologists are not entirely satisfied with the models proposed to them" (Thépenier, 1983). In spite of these facts, mainly as a result of the large gap between theoretical concepts and real processes revealed by direct observation, the actual factor of meridional exchanges, the Mobile Polar High, is still not recognized.

The Mobile Polar High: the key factor of weather

At a statistical scale the "intrahemispheric exchanges between polar and temperate latitudes" were emphasized by Christy et al. (1989) who analysed the "large-scale redistributions of atmospheric mass". But the actual vehicles of these exchanges, namely the Mobile Polar Highs, are not yet recognized. The meridional aerological exchanges, from the poles towards the tropical zone are chiefly made in low levels, and forced in the opposite direction, by the Mobile Polar Highs, or MPHs (Leroux, 1983, 1986, 1990, 1991; Comby, 1990, 1991; Alavoine, 1991; Barbier, 1991)

MPHs are the result of the downward air motion over polar regions, in connection with the permanent negative energy balance at the surface. Cooling, more intense in winter, creates an inversion, according to the synoptic situations, which is observable in the Arctic area below 2000 m. This "Arctic inversion is maintained in its normal position and intensity both by surface cooling and by subsidence, as well as by warm air advection aloft" (Vowinckel et al., 1967). Such an aerological stratification, with a southward direction in the low levels, and polewards above, is also mentioned, for example, by Thompson et al (1991) near Spitsbergen as an "Arctic front" which moves southwards. Above Antarctica (as above Greenland), where the "katabatic winds are a common feature of the lower atmosphere" (Parish et al , 1991), the same superposition of

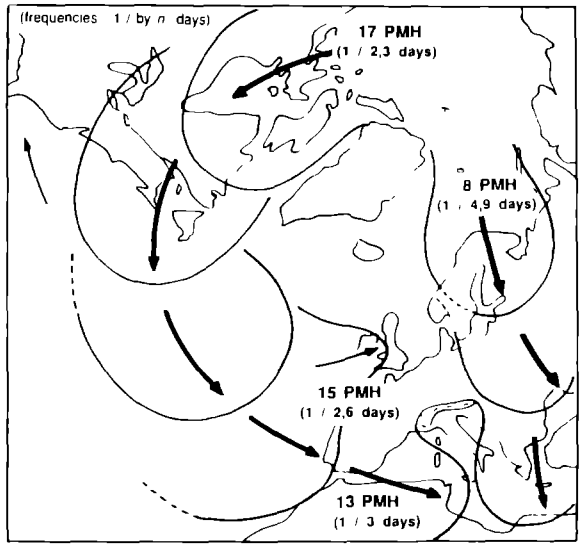

Fig 1. Mobile Polar Highs paths from December 18, 1989 to January 25, 1990 (frequencies. $1/n$ days)

opposite wind directions is observed (White et al., 1967), but the boundary is at a higher altitude (at about 3000 m), as a result of the surface elevation.

Relatively homogeneous cold airmasses are continuously "ejected" from high latitudes. As an example of MPHs dynamics, Fig. 1 shows that, from December 18, 1989 to January 25, 1990 (during 39 days), 25 MPHs were observed in the Arctic/North America/Atlantic Ocean/Europe and Mediterranean area, seventeen (1 by 2.3 days) had an initial "American" path, and eight (1 by 4 9 days) had an initial "Scandinavian" path (Leroux, 1991c) Cold air ejections organize themselves into mobile high pressure lenses, with a coarsely circular form, like a "water drop", of broad size (about 2000 to 3000 km in average diameter). But the air lenses are thin, 1500 m thick on average (Fig. 2), varying with individual cases, season (the maximum power occurs in winter), and latitude (as a result of the progressive air spreading).

They propagate, roughly from west to east, with a variable meridional component (this latter may be prevailing, as in a "Scandinavian" path). Their path is strongly governed by topography in connection with the mobile airmass thickness and elevation of relief. As a result of their absolute or

relative density and their dynamism, they force around them the uplift and the polewards deviation of the surrounding (less dense) airflows With these deflected airflows, they form a mobile "dipolar vortice" consisting of an anticyclonic branch (i e., the Mobile Polar High), and a cyclonic branch (i.e., the low or "cyclone"). Figure 3 shows a quasi-ideal organization of cloud formations connected with a MPH, the pattern being more frequently modified by interferences between MPHs Experimentally such a pattern moves "horizontally along a straight line, without any appreciable changes in its shape" and the dipole appears "to be very stable" (Van Heijst et al., 1989) The dipole formed by a Mobile Polar High also appears to have a very high stability, and it maintains itself during the thousands of kilometers of its trajectory. By reason of divergence, friction, channelling by orography, the MPH becomes progressively less coherent, until its resulting fragmentation

As much as the MPH moves equatorwards, the amplitude of the deviated circulation increases. As shown on Fig. 4, the confluence line between cold and warm air progressively withdraws from the MPH center. The MPH, the ahead peripheric low pressure corridor, and the "cyclone" or "polar low" are then progressively dissociated in the space In the same time, as a result of the MPH equatorwards motion, the deviated airflow origi-

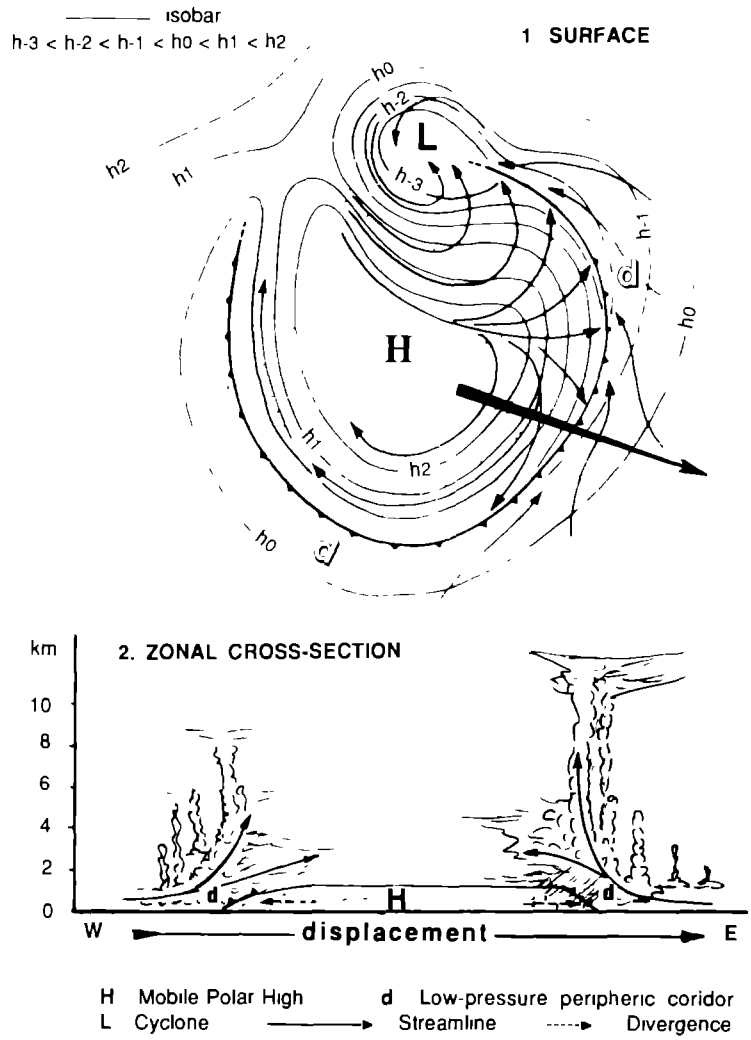

Fig 2. The Mobile Polar High, surface and vertical structure *1* Surface *2* Zonal cross-section

Fig 3 April 28, 1986, 12H00 TU, VIS, METEOSAT 2, CMS, Lannion

nates from warmer regions and carries away polewards more sensible and latent heat, especially when the confrontation occurs over oceans Lows, which are forced by dynamical convergence and ascent of the anterior "warm" air (warm, in absolute or relative value), are therefore a consequence of the displacement and divergence of MPH, eventually in connection with local factors (as relief) able to increase the upward air motion. Lows are consequently all deeper as the MPHs, firstly because they are strong or rapid and therefore able to force the ascent, and secondly as the volume and quality of deviated airflow is able to supply energy for the ascent of air around the MPH and above its margins. Intensity of the resulting weather depends on the season, i e. on the power of the MPH to disturb the surrounding circulation

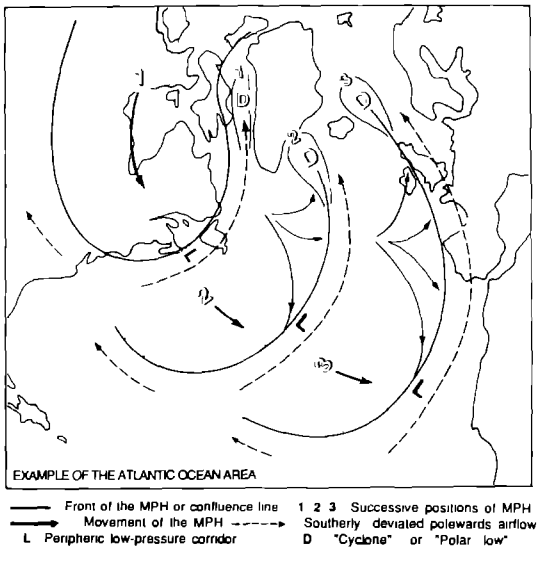

Fig 4 Wind field connected to the movement of a MPH example of the Atlantic Ocean area

The relationship. strong MPH/deep low (or inversely: weak MPH/less deep low), observed at the synoptic scale as at the seasonal scale (Leroux, 1986, 1990, 1991), has been verified (indirectly, through the SSTs) on a statistical scale in the northern Atlantic Ocean by Kushnir (1991) who noted that "the years with warm SSTs were characterized by lower than normal pressure south of the mean position of the Icelandic low, while the opposite situation tended to prevail in the years with cold SSTs" Trenberth (1990) has also ob-

served "pressures 7–9 mb lower in the Aleutian Low", and "about 6 mb higher" in the Northern Atlantic at the place where is located the so-called Azores high, in January, on northern hemisphere pressure maps for the 1945–1977 and 1980-1986 periods, the latter period corresponding to a cooling trend. The analyse by Flohn et al. (1990) of the 1961/1962–1987/1988 period pressure trends over the Pacific and Atlantic Oceans, highlights the "rise of kinetic energy" and for example in winter over the Atlantic area, shows that "the 26-year trend is remarkable", with a large area of pressure fall up to −6 hPa at the SE coast of Greenland, which contrasts with a "rising pressure in the Atlantic south of 47°N.. ". This relationship is also observed in the Northern Pacific area where, "during the cold season, the Aleutian Low. deepens remarkably, by 9 hpa, during the 22-year period" (Flohn et al., 1990) This relationship has also been empirically revealed in China in the past 2200 years, from 250 BC to 1900 AD by Wang (1980) who, even if for him "the exact cause for this is not known", remarked that "the high frequency of winter thunders tends to be associated with colder climates". As a result, at the statistical scale, a deeper "Icelandic" or "Aleutian" low signifies that the MPHs, which governed the depth of the lows, were themselves stronger during the according period.

In summary, the unceasing procession of MPHs, the poleward deviation of the surrounding airflows and the confrontation with the rised airflow around the "front" surface of the dense air lenses, are responsible for the weather variability and pluviogenesis in the high and middle latitudes. This perpetual forcing is responsible for the exportation—by coherent airlenses—of cold polar air toward the tropics on one hand, and for the poleward transfer of sensible and latent heat from middle and low latitudes, on the other hand Penetration of MPHs towards the tropics, which depends on the season, governs the intensity of energy supply from the tropical zone In winter, when their power is greatest, the MPHs displace farther equatorwards and force an intense and compensatory polewards airflow deviation. In summer, the exchange intensity weakens, the MPHs are less cold in absolute and relative value, and smaller, while their paths are displaced polewards (Leroux, 1990).

Main paths of Mobile Polar Highs and circulation in troposhere low levels

Displacement of MPHs, usually eastwards with a varying equatorwards component, is governed by relief. Because the cold air of MPH is unable to rise, the influence of orography is depending on its own elevation, on the respective sizes of relief and MPH, and on the direction of MPH movement in relation to the relief orientation. Relief acts therefore on different levels, on the local level, as at Taiwan where the "average ridge of 2500 m. . acts as a barrier to both the pre- and postfrontal flows" (Trier et al , 1990), on the regional level as in eastern North America with the Appalachian range (Bell et al., 1988), and up to the global level as the canalization of a part or even the entire MPH. At the scale of the Alps, the consequences on air circulation are already critical, because the MPH is cut in two parts. One part moves eastwards along the northern side of the range towards central Europe, and eventually the eastern Mediterranean basin, supplying then the "bora" and "meltemi" winds The other part is blocked by the Jura–Alps range and enters directly the western Mediterranean basin, often roughly amplified by orographic channelling, under the form of the strong "cierzo", "tramontane" and "mistral" winds (Leroux, 1991a, Barbier, 1991).

In the northern hemisphere, MPHs departure from the Arctic basin is influenced by Greenland, its mean altitude of about 2135 m being superior to the MPH thickness, which forces a preferential departure of airmasses towards North America and then after the Atlantic Ocean Movement is also canalized in central North America (on the western side of the path) by the Rocky Mountains, which also block the eastward motion of the Pacific MPHs. This phenomenon has been observed for the connected "cyclones" by Zishka et al (1980) who remarked that "the Rocky Mountains are a barrier to cyclones penetrating eastward from the Pacific". This relief influence is recognized, empirically and at a statistical scale,

by Christy et al. (1989) when they observed that the "hemispheric anomalies are mainly determined by pressure in the North Pacific, western North Atlantic, northern Asia and the Southern Hemisphere circumpolar trough", areas which precisely correspond to the starting points of MPHs

During their displacement MPHs are fragmented under the influence of friction, divergence, channelling and deviation by relief, or inversely agglutinated as a result of interferences between MPHs, slowing down and blocking by relief (Leroux, 1991c; Leroux et al., 1992). They finally enter the tropical zone under the form of various sizes "mobile anticyclonic nucleus", which then supply the low-layer trade circulation, where they are reflected in the wind and isobaric fields by the so-called "easterly waves" and westwards pressure waves (Leroux, 1983, 1988a). Figure 5 shows an example of propagation of two strong MPHs down to the equator. The first MPH (Fig 5a), was born on January 14, 1990 in the Arctic Ocean, moved over North America and across the Atlantic Ocean, and arrived in West Africa 5 days later. The second one, originating on January 16 (Fig 5b), followed it and caught it The resulting strengthening of trade provoked a low temperature, as observed by Sagna (1990), a dense dust haze, and pushed away the western surface Meteorological Equator to the Guinean Gulf from January 22 to 25, 1990 (weather analysis made from European Meteorological Bulletin and ASECNA Meteorological Department (Niamey) synoptic maps; cf. Leroux, 1991d) In western Africa the surface Meteorological Equator is usually maintained inland by thermal lows on the northern limit of rainforest (Leroux, 1983) Such a pattern (Fig. 5b) explains the partial disappearance of rainforest during the Last Glacial Maximum, when the wet monsoon which prevents an excessive warming over the trees, was replaced by the very dry and reinforced continental trade or harmattan (Leroux, 1990b)

As a result, the determination of circulation domains in middle latitudes by the conjunction of relief distribution and MPHs paths, is also responsible in the tropical zone for trade circulations. In this way, the MPH process finally reaches the scale of troposphere general circulation At the scale of great barriers, like the Rocky Mountains, the Andes, or the uninterrupted alignment from the Taurus to the Himalaya–Tibet highlands, the relief influence is prevailing and determines low levels distinct aerological domains. Figures 6 and 7 show the main domains of low levels circulation determined by interference between MPHs and relief.

* In the northern hemisphere (Fig. 6) two large areas include:

– North America (east of the Rockies)/Atlantic

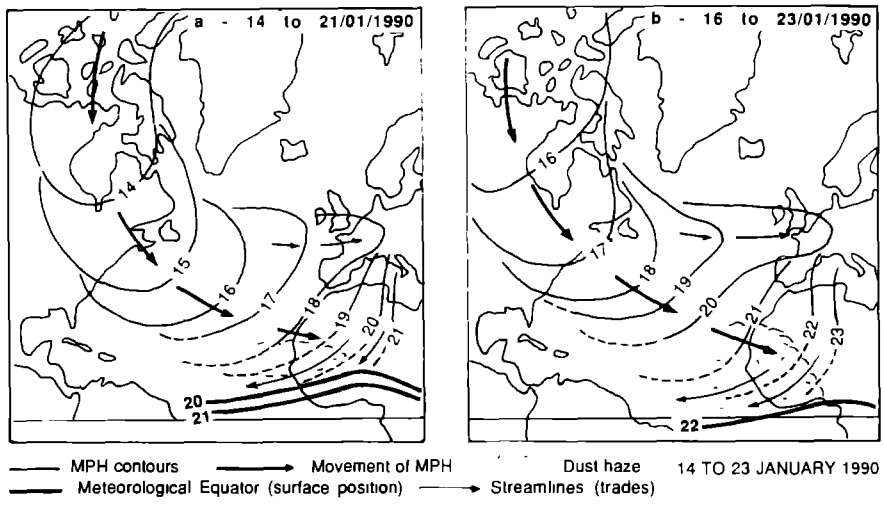

Fig 5 Propagation of MPHs from the Arctic area to the Meteorological Equator January, 14–23, 1990

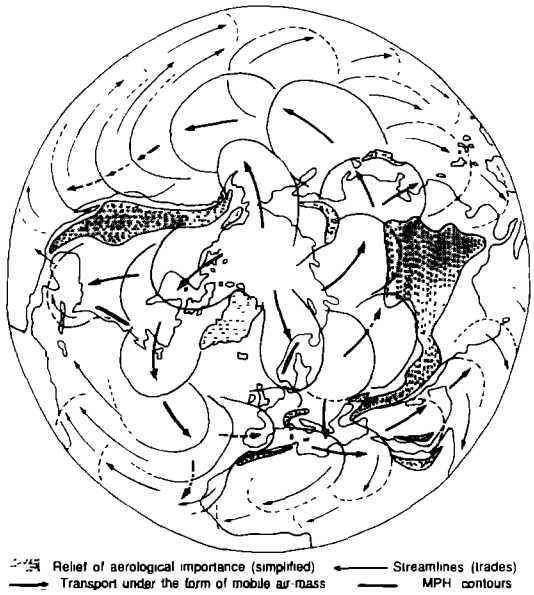

Fig 6 Paths of the Mobile Polar Highs and resulting circulation in the low levels of troposphere Northern Hemisphere

Ocean/ Europe/ Mediterranean/ Africa/ Southern Asia (south of the highlands from Turkey towards the Indian Peninsula);

- Northern Europe and Asia (north of the highlands from Turkey towards China)/ Pacific Ocean where a reinforcement is possible between Siberia and Alaska (Bering Strait)/western coast of North America (west of the Rockies).

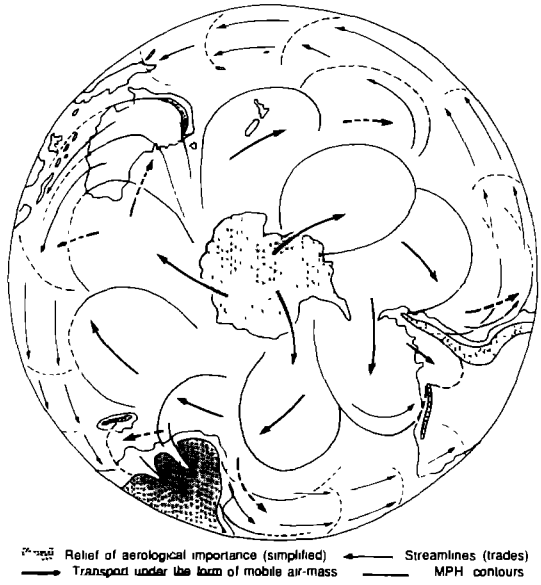

Fig 7 Paths of the Mobile Polar Highs and resulting circulation in the low levels of troposphere Southern Hemisphere

Between these two areas a connection is possible at the encounter of the "American" and "Scandinavian" paths over Western Europe (Leroux et al., 1992), while the air of Central Europe, particularly the cold winter air, can invade (between the Alps and the Turkish highlands) the eastern Mediterranean basin towards northern Africa

* In the southern hemisphere (Fig. 7) there is no relief to determine a preferential departure of MPHs around Antarctica, but the canalization is vigourously northwards, along the eastern side of the Andes, and in the south of Africa along the Namibian Great Escarpment, and even the south of Malagasy, or along the western side of the Australian Alps.

Distribution of oceans and continents explains that the mean trajectories followed by MPHs are roughly always the same. However, as a result of changes in intensity, the arrival of MPHs in the tropical zone may occur anywhere, particularly in winter when the meridional component of trajectories is more pronounced. However, the presence of continents and relief makes this penetration more frequent in the eastern side of the oceans, where the MPHs are slowed and agglutinated. This anticyclonic agglutination usually occurs at the synoptic scale, and is revealed at the statistical scale by surface pressure and wind data averages. At this mean scale, the statistical pressure centers named "subtropical highs", are defined by this arrival frequency of MPHs on the tropical zone margins. The so-called statistical or climatological highs are therefore an illustration of the MPHs power. A "stronger" high signifies that the MPHs and the meridional air and energy exchanges are likewise reinforced, and inversely a "weaker" high implies weakened MPHs and reduced meridional exchanges.

A seasonal change is observed, with changes in size and power of MPHs. In summer the mean paths move polewards and in winter equatorwards This seasonal variation modifies the latitude where the eastwards transport under the

form of airmasses (i.e the extratropical circulation) is gradually replaced by the westwards low levels linear trade circulation (i.e the tropical circulation), according to the anticyclonic rotation in separate MPHs or in an agglutination of MPHs

In summary, high latitudes are still considerably more important than supposed by Weller (1990), and are undoubtly the "key to world climate" (Abelson, 1989), if we consider the formation of cold airmasses, and their propagation as far as into the heart of the tropical zone. Such a process incite us to integrate the MPH in present and past troposphere circulation models.

Present and past troposphere circulation models

Kukla (1990) states that "there are three tests which can be used to judge the utility of the model results": simulation of the current observed climate, prediction of the increased CO_2 impact, and simulation of past climates This conclusion is hard. "it is obvious that the result of the three tests are far from satisfactory" (Kukla, 1990, p 112), particularly because "some of the processes operating in the real world climate system ..are incorrectly represented in the models". It appears therefore necessary to consider the real dynamics of meridional exchanges, and to give the MPHs their actual importance in the troposphere general circulation.

We cannot present here the details of general circulation concepts, but they usually emphasize the organization in each hemisphere in separate and closed cells on one hand along a meridional direction a polar cell, a temperate or Ferrel cell, a tropical or Hadley cell, and on the other hand some zonal Walker cells in the tropical zone. With opposite directions in the vertical plane, with direct or indirect cells, both along meridional and zonal directions, such an organization, does not show the possible communications between cells, and omits the meridional exchanges in low levels of troposphere under the form of air lenses by MPHs, and forced by them in the opposite direction.

Figure 8 presents a schematization of the general troposphere circulation. The key components are:

- Chiefly the MPH which makes the exchanges under the form of a dense air lens. It originates

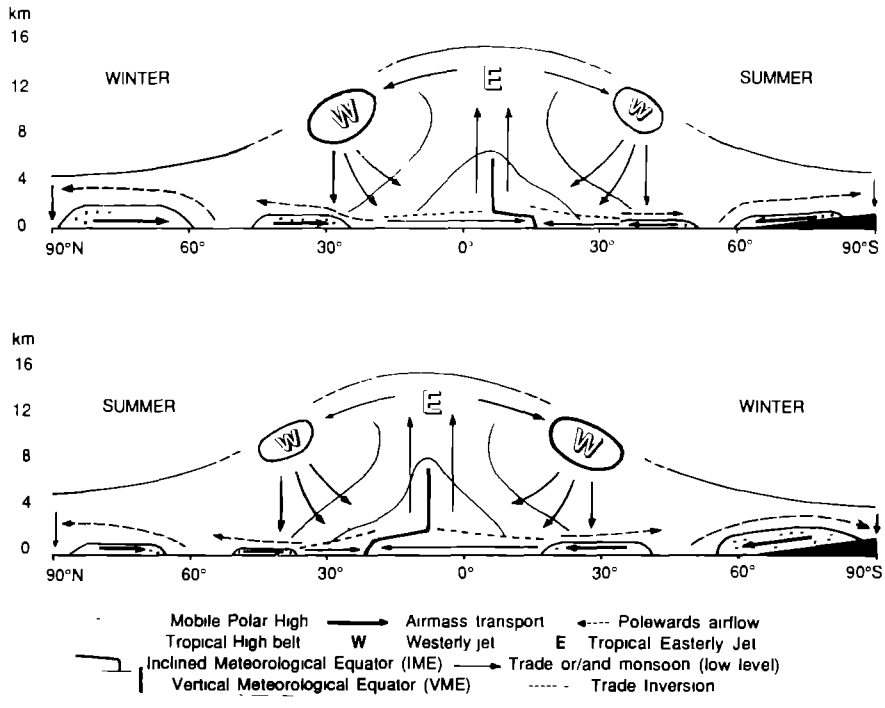

Fig 8 General circulation of troposphere· seasonal schemes

the low levels airflows and consequently determines the speed of troposheric exchanges. Its size on the schemes attempts to be proportional to its seasonal or/and latitudinal power

- Upper westerly jet depends on the intensity of energy exchanges, and is mainly forced, in connection with the latitudinal pressure gradient, by the upward motions of the mid-latitudes disturbances created by MPHs. In each hemisphere the jet is therefore stronger, more rapid, and displaced towards tropics in winter, and is weaker and displaced polewards in summer.
- Downward air-motion (or the descending branch of the "Hadley cell"), under the equatorial side of the upper jet, builts the two mid-level Tropical High belts, but in the low levels this downward contribution is by far considerably less important than the supply by MPHs. In low levels the cool and dense air of MPHs travel without any difficulty equatorwards underneath the warm subsiding air As a result the trade circulation is stratified, the two aerological layers which form the trade being separated by the trade inversion, i.e. an inversion of subsidence, of temperature and of water vapour content (Leroux, 1983, 1986c)
- Meteorological Equator (ME), with its two vertical rain-making structures (Fig. 9) The Inclined Meteorological Equator, or IME, concerns only the low levels, particularly over continents. As a result of the wind stratification this structure is frequently sterile, but may be crossed by westwards, isolated, short-lived and stormy squall lines. The Vertical Meteorological Equator, or VME, represents either the whole structure of ME, especially over oceans (Fig 9a) where it is usually known as the ITCZ (Intertropical Convergence Zone), or represents only the mid-level structure over continents or/and adjacent areas (Fig. 9b, which corresponds to the northern summer), as over tropical Africa (Leroux, 1983). This latter vertical structure concentrates the best

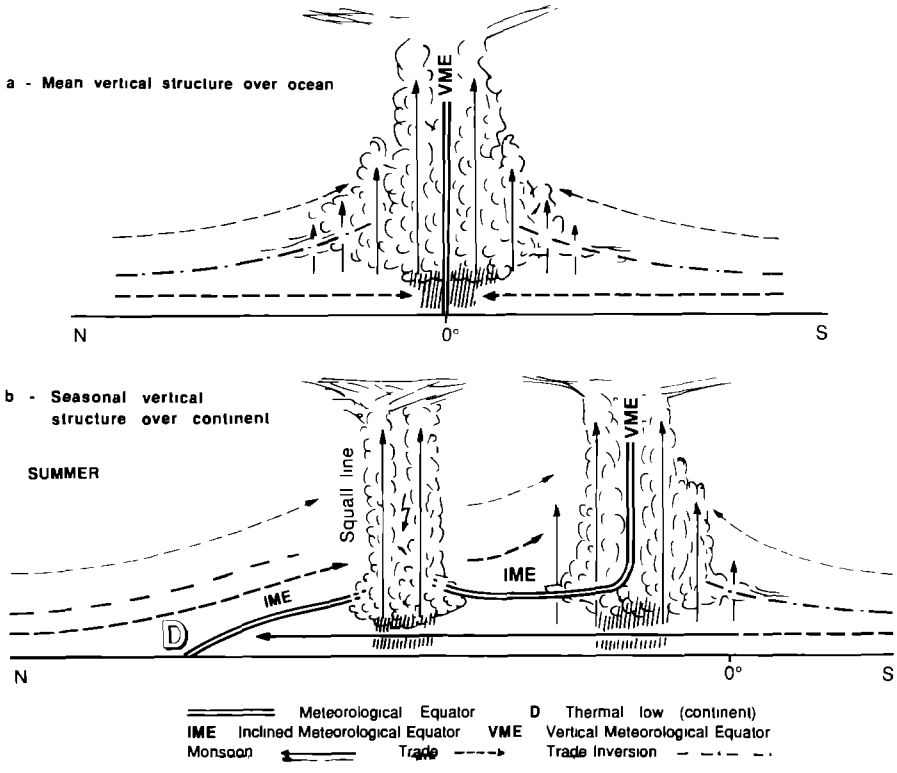

Fig 9 Vertical structure of the Meteorological Equator a Mean vertical structure over ocean b Seasonal vertical structure over continent (example in northern summer).

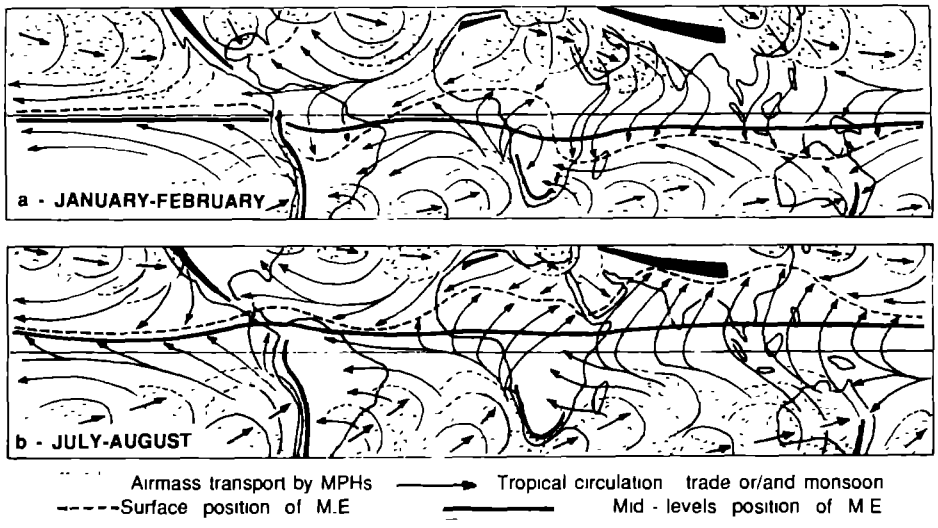

Fig 10 Airmass transport by MPHs, resultant tropical circulation and positions of the Meteorological Equator, surface and altitude: present mean seasonal conditions a December–February b June–August

structural and energetic conditions, and consequently offers the best tropical conditions to pluviogenesis. Figure 10 shows that the amplitude of annual migration is different according to the levels The VME (or ITCZ) remains relatively in the vicinity of geographical equator, while inversely the summer ME surface position moves away from it, allowing then in the low levels, under the IME structure, a large transequatorial circulation, i.e the monsoon.

Mean circulation is expressed by streamlines on the schemes, only where an average value (i.e the resultant wind) is representative of the real dynamics. Such is solely the case of the tropical zone, for trades and their eventual prolongation, the monsoons In extratropical zones the mean or resultant pressure and wind values have a very restricted significance, because the observational data is a result of the contradictory motions connected to the roughly westerly movement of MPHs Each passage of MPH forces alternately a southerly wind and then a northerly, a pressure fall and then after a rise, while often wind is absent in the heart of the migratory high. In Figs 6–12 the airmass type circulation in polar and temperate zones, i.e the MPH with its anticyclonic rotation and ahead or aloft the cyclonic polewards airflow, is therefore clearly distinguished from the linear type circulation, i.e the relatively steady streamlines, restricted to the tropical flows, trades or monsoons.

Figure 8 emphasizes that the climatic fact is seasonal. In the winter meteorological hemisphere, exchanges are intense with strong MPHs, and intense polewards deviated airflows and in high levels the westerly jet-stream reaches its

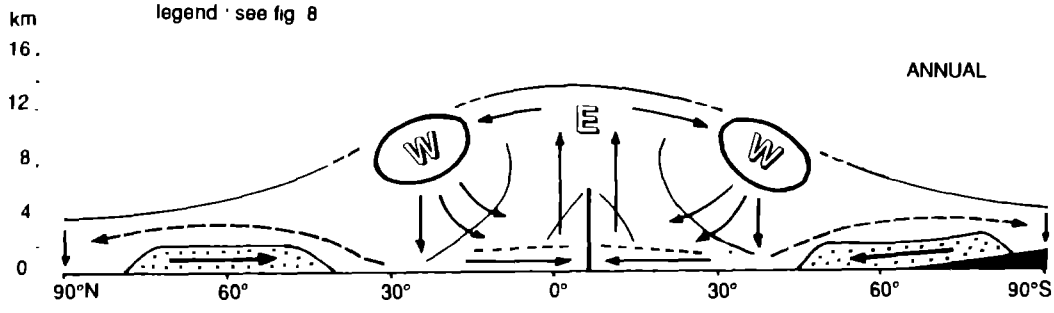

Fig 11 Rapid general circulation mode (high polar energy deficit)

highest speed, and its lowest latitude. The winter meteorological hemisphere is then powerful and spreads at the expense of the summer meteorological hemisphere This advantage is reflected by the position of the Meteorological Equator (Fig 10), which mainly depends on the dynamics of airflows of one meteorological hemisphere, but also on the power of the other meteorological hemisphere, either able to push them away, or inversely to attract them by means of thermal lows, usually in summer (which can only act on the low levels: Fig. 8)

These seasonal circulation schemes, strong (or weak) in the winter (or summer) meteorological hemisphere, exemplify two global circulation modes, one rapid, one slow, determined by the intensity of the polar energy balance deficit (Leroux, 1986b; 1988b). The following schemes are considered, for convenience, only at the mean annual scale (Figs 11 and 13).

Rapid general circulation mode (Fig. 11)

This circulation mode corresponds to a global cold situation characterized by a high thermal deficit in polar latitudes throughout the year, amplified in northern hemisphere winter by vast continental cold areas and extensive land and sea-ice cover The MPHs are strong, widespread and maintain low temperatures and coherence, along more meridional paths. They are able to force a direct and intense polewards transfer of tropical energy. Middle latitudes disturbances are violent, as a result of the strong exchanges intensity and temperature contrasts between airmasses. Low levels airstreams are rapid both in temperate and tropical regions.

The entire troposhere experiences a general acceleration. Upper levels westerly jets and the related subsidence are reinforced, migrating equatorwards. As a result of enlargement of the polar zone, and displacement of the MPHs paths and of temperate zone towards tropics, the tropical zone is strongly reduced The opposing dynamisms of the hemispheres restrict to a narrow belt the annual translation of tropical rain-making structures, as the Meteorological Equator, now unable to reach the tropical margins (Fig 12). The anticyclonic action centers are more vigorous, particularly over the cold continents where the movement of MPHs is frequently slowed, and even blocked in cold continental high pressure agglutinations. In this situation the northern meteorological hemisphere comparatively spreads, at the expense of the southern one, and the Meteorological Equator is displaced south of the geographical equator (Fig 11).

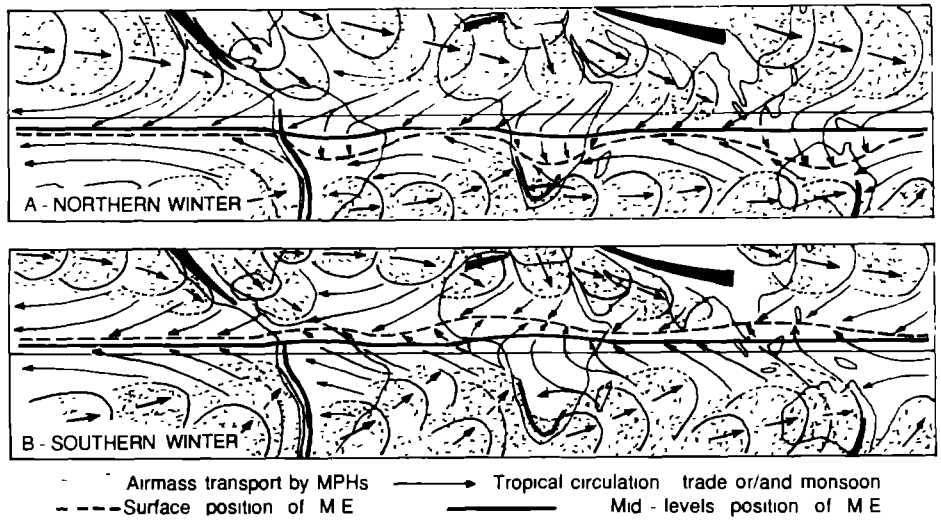

Fig 12 Airmass transport by MPHs, resultant tropical circulation and positions of the Meteorological Equator, surface and altitude, mean seasonal conditions connected with a rapid circulation a Northern winter b Southern winter

Slow general circulation mode (Fig. 13)

This mode of circulation corresponds to a reduced thermal deficit in high latitudes The power of MPHs is reduced, their mean path remain polewards and the frequency of direct and intense Tropics/Poles air exchanges is low. The winter pressure thermal strenghtening over

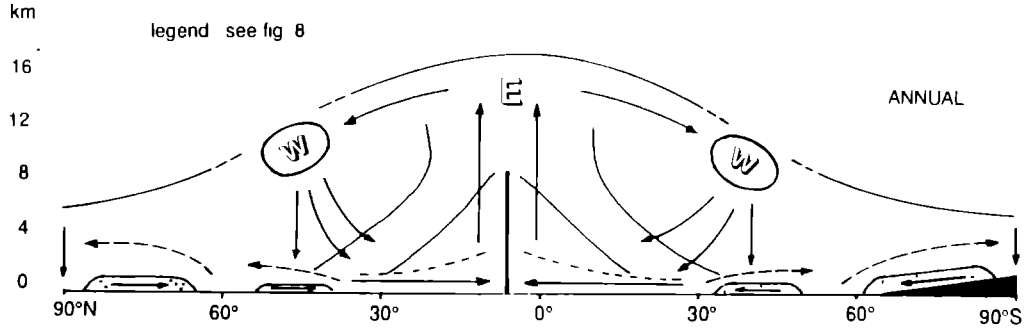

Fig 13 Slow general circulation mode (low polar energy deficit)

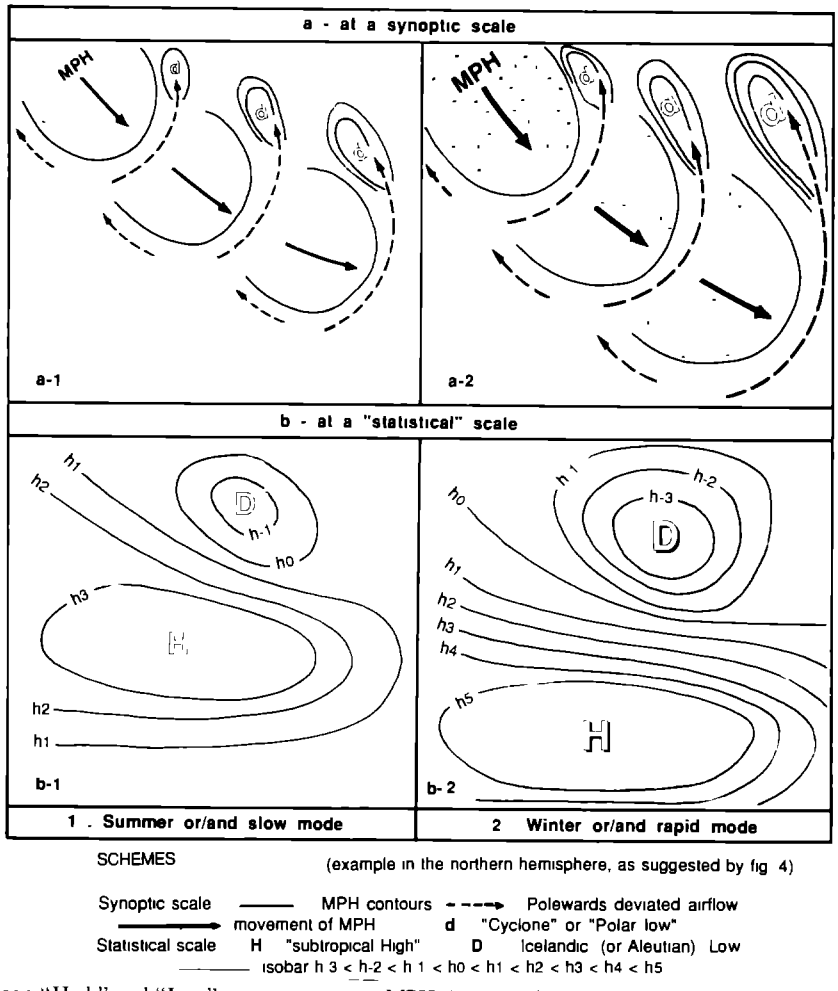

Fig 14. Relation between "High" and "Low", in connection to MPH dynamics (example in the northern hemisphere, as suggested by Fig 4).

northern continents is decreased, while the continental "blocking" situations are less frequent, only reserved to the heart of winter. In mid-latitudes, intensity of disturbances and the general dynamics of low level airstreams also weaken. As the tropospheric circulation and the upper westerlies slowing down, the downwards air motion diminishes above the Tropical High belt. The tropical zone is considerably widened, the Meteorological Equator, with its rain-making structures, has an amplified annual migration, allowing strong seasonal contrasts, and large transequatorial water transfers by monsoons in connection with an increased precipitable water-potential (cf Fig. 10, the present conditions being still roughly close to a slow circulation mode) In this situation the southern meteorological hemisphere is relatively more dynamic, spreading itself at the expense of the northern one, and displacing the mean position of the Meteorological Equator to the northern hemisphere (Fig 13).

Some resulting key features are to be highlighted:

– In each hemisphere, in a rapid mode, the westerly jet is strong and displaced equatorwards (as, all things considered, today in winter), but weak and polewards in a slow mode (as, all things considered, today in summer) It is therefore unlikely that the "large 3-km thick Laurentide ice sheet" would have been "responsible for splitting the flow of the jet stream in winter across all of North America .." (COHMAP, 1988), because these surface conditions are unable to -directly-affect the upper levels, and chiefly because the jet was displaced at that time (18 ka) largely south of the ice sheet, especially in winter. In the same way, if a "very strong westerly flow" (COHMAP, 1988) appears very similar at 18 ka, and still at 12 ka, a "stronger" westerly flow again at 6 ka, and still more "in july", is obviously in the wrong

– On a "statistical" scale, when meridional exchanges are intensified during a rapid mode (as, all things considered, in winter on a synoptic scale· Fig. 14a-2), the resulting mid-latitudes lows (Icelandic or Aleutian) are deeper, and the "subtropical highs" (of Azores, or Hawai. .) are stronger, and displaced equatorwards (Fig. 14b-2) Inversely when exchanges intensity is reduced during a slow mode (as, all things considered, in summer on a synoptic scale: Fig 14a-1), the lows are less deep and the "subtropical highs" are weaker than present, and displaced polewards (Fig 14b-1). Consequently, a "stronger low/ weaker high" association, as proposed by COHMAP (1988) to explain the 18 ka conditions,

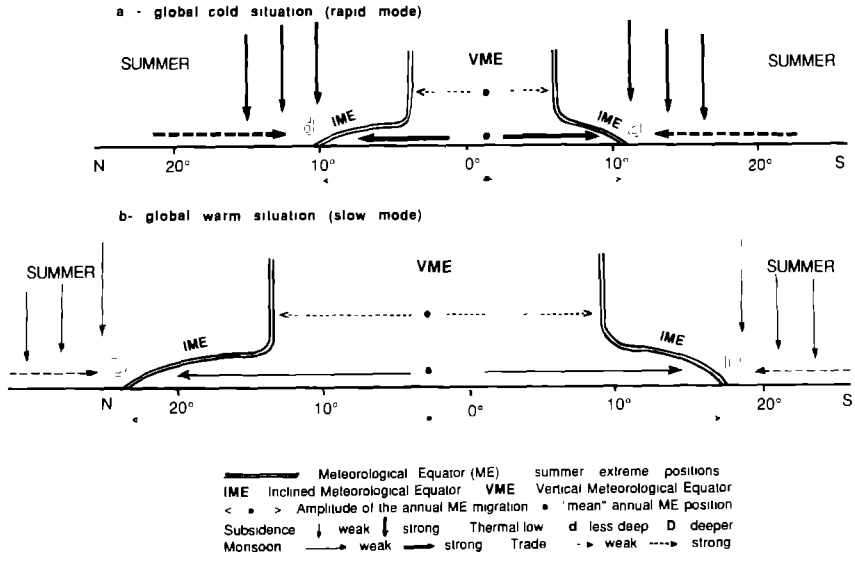

Fig 15 Differenciated migration of the Meteorological Equator schemes a. Global cold situation (rapid mode) b Global warm situation (slow mode)

appears hypothetical. In the same way the interpretations which consider that, a "stronger subtropical high" was associated to the 9 ka and 6 ka situations, and on the contrary that a "weaker subtropical high" was related to the 18 ka and 12 ka conditions (COHMAP, 1988), are undoubtly in the wrong

- In the tropical zone some circulation features may appear ambiguous or/and even paradoxical. For example, what is the real meaning of a "weaker" monsoon linked to the 18 ka conditions (COHMAP, 1988), when at that time the monsoon was precisely more rapid (and in fact "stronger"), but was blowing in a restricted tropical belt . It appears necessary to distinguish clearly, on one hand the wind speed, and on the other hand the extent of the area covered by the tropical airflows:

Strenghtened MPHs during a rapid mode gives more power to trades and monsoons But despite this strenghtening, the area of the tropical flows is considerably reduced, and chiefly this one of the cross-equatorial monsoons, as a result of the extratropical zones expansion, of the tropical zone contraction, and of the Meteorological Equator annual displacement reduction (Figs. 12 and 15a)

Weakened MPHs during a slow mode reduces the trades and monsoons speed. But the tropical zone is considerably dilated, the annual displacement of the two Meteorological Equator structures being then strongly enlarged (Figs 10 and 15b)

Consequently, the migration and activity of Meteorological Equator is an evidence of the antagonistic northern and southern forces supplied by MPHs

In a rapid mode, intensity of the dynamical convergence is strongly increased along the Meteorological Equator, which is however contained in a narrow belt, close to the geographical equator

In a slow mode, the weakening of tropical flows is balanced by the attractive power of the continental thermal lows, which follow the sun zenithal motion. These thermal lows strongly amplify the displacement of ME in surface and low levels, i.e the inclined structure (IME) But the movement of the vertical structure (VME), which does not closely depend on the surface conditions, is comparatively less amplified (Fig. 15)

As a result of these particular features, the tropical climate patterns cannot be only explained by reference to the so-called "ITCZ", usually (even solely) considered over oceans, without precise attention to the real ME vertical structures The undifferentiated "ITCZ" concept is therefore unable to explain the tropical changes, chiefly over continents, and still less when, as estimated by the COHMAP (1988), the "ITCZ" stayed roughly at the same place over the Indian/Pacific Oceans, in the vicinity of the geographical equator, in January like in July, at 18 ka, and again at 9 ka, as in the present ..

These schematic troposphere circulation models emphasize the control of the general circulation intensity by the polar latitudes thermal balance. It appears therefore necessary to examine the external control of climate variations, i.e. the insolation changes, especially in high latitudes

Insolation changes in high latitudes during the past 30 ka

Total terrestrial insolation has only varied by 0 6% in the last 10^6 years (Genthon et al., 1987). Such an amplitude appears very inadequate to explain the considerable past climate changes, while an estimate on the global scale has a limited significance The changes are relatively minor in equatorial or even tropical latitudes. For example, at the latitude of the northern Tropic (23°N, Fig. 16), the insolation has varied from

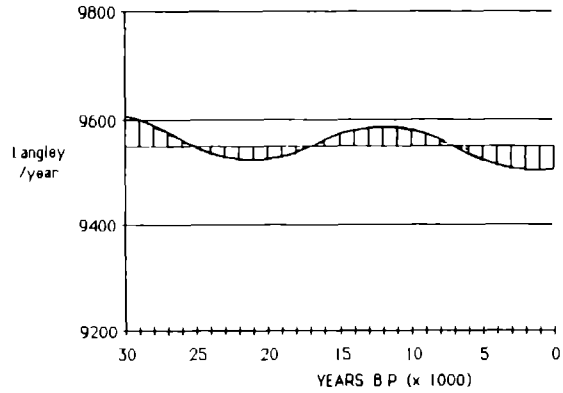

Fig 16 Annual insolation at 23°N (O K Davis)

9523 Ly to 9587 Ly during the past 30 ka, ca. only 64 Ly, or 6.7‰. Figures 16 and 17 are established with data calculated by O.K. Davis (1988, and pers. comm.). This value is indeed unable to explain the paleoclimatic changes in tropical latitudes This insignificant variation shows, firstly that thermal changes in the tropical regions were not native but were one result of changes in extratropical zones and secondly signifies that Tropics were always able to furnish sensible and latent heat to the meridional exchanges

The insolation changes were much greater in polar zones, as revealed by a number of studies since M Milankovitch, and as demonstrated here by O K. Davis (1988). Figure 17a shows the reciprocal variations of north and south polar summer insolations. During the last 30 ka, insolation at the North Pole had the greatest range: 4050 Ly at 24 ka to 4573 Ly at 11 ka, i e a 523 Ly rise in annual values, or a 13% rise of minimum value Two maxima are observed in the South Pole zone: insolation varied from 4052 Ly at 30 ka to 4470 Ly at 3 ka i.e. a 418 Ly rise in annual values, or a 10% rise of minimum value.

The two polar insolation curves cross three times, each crossing corresponding to equal values at the Poles, but at different strengths (Fig 17a). At 28 ka, both curves are relatively low and cross at 4105 Ly. At 17 ka, they cross at 4339 Ly (3% higher than today in the North, 2% lower in the South). At 6 ka, the curves cross at 4423 Ly, the highest equal value.

The polar insolation changes, more representative than a global estimate, determine two extreme synchronous polar thermal regimes: one cold, around about 28 ka (equal low insolation) and the other, warm around about 6 ka (equal high insolation) Figures 11 and 13 illustrate respectively the tropospheric, rapid or slow, circulations connected with these synchronous polar situations.

Figure 17b shows that the northern and southern variations were not exactly synchronous, the excess rising to about 250 Ly, i.e. three times the insolation increase between 17 ka and 6 ka (84 Ly), giving by turn an advantage to one meteorological hemisphere over the other. As a result, by a combination of the two modes, more precise models can be imagined. For example, if we consider only the insolation conditions, at about 11 ka circulation was in a slow mode in summer in the northern hemisphere, while in the southern meteorological hemisphere the maximum southern deficit forced a relative rapid circulation mode, and gave it a strong geographical advantage

Evolution of polar insolation does not closely fit the climatic variation. for example the Last Glacial Maximum at about 18 ka does not correspond to the lowest insolation values, which were then nearly similar to those of today (Fig. 17a). Polar insolation cannot explain alone the past climate, but governs the power of MPHs, which on turn commands the surface boundary condi-

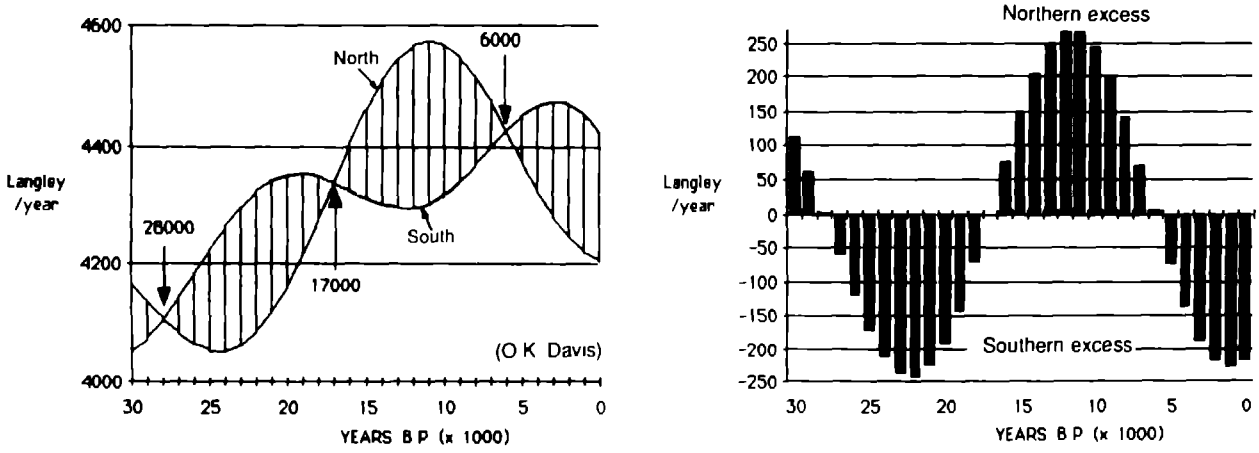

Fig 17a Annual insolation at 85°N and 85°S (O K Davis) b Annual insolation difference 85°N–85°S

tions in the high latitudes, chiefly in the northern hemisphere.

Paleoclimatic evolution of the last 30 ka: a MPH concept reassessment

Palaeoclimatic changes are the result of the main aerological and geographical following factors (apart from the oceanic conditions)

- the key control of polar latitudes on the birth and dynamics of MPHs (Figs. 5 and 6),
- the insolation changes in the high latitudes (Fig. 17), and the surface conditions, as the albedo, able to modify the insolation efficiency,
- the key forcing of MPHs on the two directions of meridional exchanges, both directly equatorwards and indirectly polewards (Figs. 4 and 8),
- the relatively constant insolation in the tropical zone (Fig 16), which permanently provided sensible and latent heat to meridional exchanges, forced by MPHs more or less directly polewards,
- the key control of MPHs, on the circulation intensity, on weather, on the distribution of aerological vertical structures and of rain-producing disturbances, directly in temperate zones (Figs. 2 and 3), and indirectly in the tropical zone (Figs. 5, 8 and 10),
- the geographical factors which determine, the paths of MPHs and therefore the global conditions of low levels circulation (Figs 6 and 7), and the surface conditions able to control the thermal convection and to create thermal secondary action centers, particularly thermal lows in the tropical zone

All these components concern large scale phenomena, but the past changes are also under control of a physical state particularity of water, which commands frost and therefore the type of precipitation With one "little" degree less, rain is replaced by snow, a no-immediatly recoverable water potential, and for other few degrees, snow does not melt in summer (or inversely). This particularity must be considered in the very sensitive high latitudes.

The period of progressive insolation deficit in polar regions inducing the last glacial, had began around 40 ka (Andrews, 1982), and had culminated around 24 ka in the northern hemisphere (Fig 17a). As a result, for example in Siberia "the greatest cooling within the Late Pleistocene started .. after 27,000 to 24,000 years ago" (Velichko, 1984). In polar and temperate regions the native water-vapor potential, already limited, decreased in connection with the temperature fall, but the power of MPHs was gradually increasing.

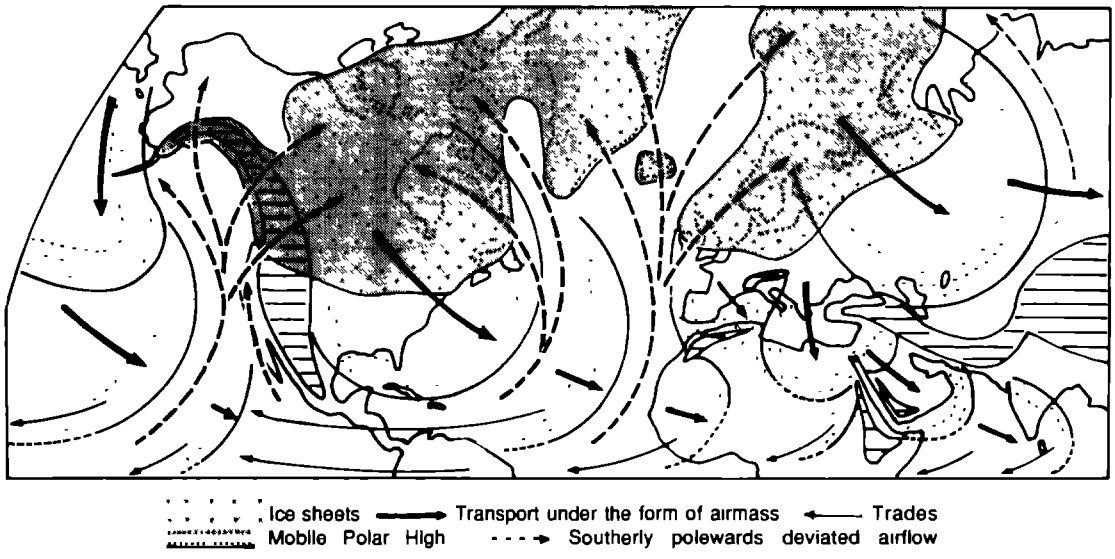

Fig 18 Paleometeorological conditions during the Last Glacial Maximum

A precipitable water-vapor potential was always available in the tropical zone (Fig 16), and the reinforced dynamics of MPHs became progressively able to transfer an increasing part of this potential poleward (Figs 4 and 14a-2). Soon tropical water-vapor was preferentially and directly transported towards temperate and polar zones. The increasingly MPHs powerful deviated polewards an increasing volume of tropical energy, more regularly and more strongly Therefore heavy precipitation fell in the high and middle latitudes, more and more often as snow. The present conditions of snowstorms formation along the northeastern coast of the United States (Kocin et al., 1990), or of the dramatic "blizzard of 88 ", i.e , 1888 (Kocin, 1988), show the reality of the process connected with strong MPHs They also reveal that only small deviations (all things considered) from the present weather state were needed to produce glaciation. In a first time heavy winter snowfall melted during other seasons, chiefly by reason of heavy rains falling above snow or ice, a fall which speeds up the melting of snow.

With continued cooling, and with the high reflective ice amplifiing the effects of insolation decrease, summer ablation progressively vanished, and snow fell all year long in the high latitudes. Strong MPHs diverged from the ice sheets, the spreading of cold air being intensified by vigorous katabatic winds (soon stronger than over the present Antarctica or Greenland) Air stratification above ice sheets progressively prevented low levels from direct contact with the advected warm air, and the lower cold air protected their southerly margins from melting. Figure 18 highlights that not any stable "glacial anticyclone" with "surface easterly winds" (COHMAP, 1988) permanently settled over the North American and Eurasian ice sheets. On the contrary the gradual elevation of ice, and the resulted slopes, favoured the unceasing MPHs departures, the previous Arctic starting point of MPHs towards the Atlantic Ocean being then southwards displaced.

At this meteorological stage, the tropical water-vapor potential was directly transported polewards and strongly concentrated by the high frequency of MPHs blockings into two restricted areas. The first blocking occurred over the Eastern Pacific Ocean and resulted from the encounter by the Pacific MPHs paths of the meridian relief (Fig. 6). This barrier, in connection with the front side of MPHs, forced regularly and strongly northwards the warm and wet air of the tropical eastern Pacific Ocean (and partly of the western Atlantic, and Gulf of Mexico, having crossed the isthmus), along and above the western side of the Rocky Mountains (as, all things considered, usually today towards Alaska) The second blocking occurred in the Atlantic area, where the "American" MPHs forced polewards airflow In the vicinity of western Europe they were blocked by the colder and denser "Scandinavian" MPHs, or/and by the continental agglutination In the temporary low pressure corridor between MPHs the northwards deviation of the tropical potential was then accelerated As a result, by reference to the statistical "Icelandic low", Labeyrie et al. (1985) thought "that a strong cyclonic cell, centered approximatively 55°N and 15°W, was active during most of the last ice-age maximum" In fact the MPHs were themselves very strong and the southerly airflow was vigorously lifted above the MPHs and above ice sheets A present comparable situation (all things considered) occurred during 39 days in December 1989–January 1990 (Fig. 1): cold temperatures over North America (Janowiak, 1990), corresponded to above normal precipitations over Scandinavia, while the rest of western Europe, overlapped by a cold agglutination of MPHs, suffered from a pronounced rain deficit (Leroux, 1991c; Leroux et al , 1992) At the same time northern Africa received rainfall in excess, in connection with a southwards deviated MPHs trajectory (Leroux, 1991d) Identical anticyclonic agglutinations lasted over Western Europe, for 77 days during the 1988–1989 winter, for 86 days during the 1989–1990 winter, for 52 days during the 1990–1991 winter, and for 111 days during the 1991–1992 wintertime (Leroux et al , 1992). Such meteorological conditions (Figs. 12 and 18), all things considered, have induced heavy snowfalls over African mountains in the past, as over Tibesti or Ethiopian highlands, and supplied

"névés" on the western side of Assekrem in the Hoggar (Rognon, 1989).

In the Arctic area "temperatures were about 8°C lower than at present" (Maxwell et al., 1989), and cooling of high latitudes displaced climatic zones towards tropics At the eastern Asian exit of MPHs (Fig. 6), the "conditions in the southern Sea of Japan at these times were similar to those who exist today in subpolar regions far north" (Moorley et al., 1986), and as demonstrated by the character of sedimentation in the South China Sea "at the close of the last glacial period" the conditions were "coincident with the changes found at high latitudes" (Broecker et al., 1988). The annual mean temperature "was 6°C lower than present in Qingshai-Xizang (Tibet) plateau, 6–9°C lower in NE China and Japan, 6°C lower in E China and central Japan, and 4°C lower in Taiwan Island" (Tianchi, 1988)

As a result of the intensified circulation (Fig. 12), in Africa the Saharan belt moved southwards to attain 13–14° of latitude N. Eolian transport increased in connection with a decreased precipitation, but chiefly due to a strong wind acceleration (Leroux, 1987, 1991b), which then produced the Ogolian-Kanemian ergs, much further South than nowadays (Faure, 1969; Sarntheim, 1978, Servant et al , 1980; Petit-Maire, 1984; Talbot, 1984; Hooghiemstra, 1986). Dune building also occurred in southern Africa, chiefly in the Namibian area where ergs advanced northwards (Van Zinderen Bakker, 1980, 1982; Heine, 1982), the tradewind being roughly channelled by the Great Escarpment. Strenghtening of the northern and southern continental trades, induced an almost-disappearance of the rainforest (Maley, 1987), which survived in orographic shelters For example, the Guinean Ridge on its western side (coastal Liberia/Sierra Leone), or the Adamawa plateau on its southern side, were both able to protect the trees from the presence of the drying northeastern harmattan (Fig. 5), while the Congo basin was also invaded by the southeastern continental trade (Leroux, 1990b). For similar reasons the same withdrawal towards refuges also concerned the Amazon forest (Servant et al., 1993) Wind acceleration was globally observed, not only in the low levels but in the whole troposphere, as revealed by the high concentration of continental aerosols in the polar ices (De Angelis et al., 1987; Revel, 1992).

In the progressively reduced tropical zone, temperature and evaporation remained high But in proportion as cooling by MPHs was globally propagating, the annual amplitude of discontinuities was slowly restricted, while the spatial dispersion of rain was gradually concentrated in the center of the zone, itself displaced southwards (Figs. 12 and 15a). However, even in the narrow belt close to the Meteorological Equator, rainfall was decreasing, in spite of the strenghtening of dynamical convergence. This general diminution (Kutzbach et al., 1985) appears paradoxical with such a concentration of dynamical and structural rain-making favourable conditions, even if a small decrease of temperature was in the same time observed. This rainfall decreasing cannot be clearly understood without taking into account the deviation—in fact the real "capture" by MPHs—of the tropical water-vapor potential towards the high latitudes. Tropical airflows were more intense, but their spreading area was limited (Fig. 12). The transequatorial drifts (monsoons) were especially restricted and, as the margins of tropical Africa, southern Asia was not reached in summer by the southwest monsoon. Northwest India was then "cold and dry" (Hashimi et al , 1986; Pant et al , 1987) In the North Indian Ocean was only observed "a very weak southwest airflow, a great reduction of summer monsoonal rainfall" (Van Campo, 1986), while "weaker monsoons from SW" (Prell et al., 1986) concerned only the western Arabian Sea and Horn of Africa Inversely, the northern trade, wrongly called "NE monsoon" or "winter monsoon", supplied by stronger than present MPHs following a Mediterranean/North African and Arabian path (Fig. 12), "was the dominant feature" (Fontugne et al., 1986), and this trade circulation "was stronger" than at present (Sarkar et al., 1990).

Over northern polar regions insolation was higher than to-day around the 17 ka equilibrium between the northern and southern hemispheres (Fig 17) But in spite of this increase of insolation, warming was slowed by ice accumulation,

and also by reduced atmospheric CO_2 content (Barnola et al., 1987). The dynamism of the northern meteorological hemisphere remained dominant, due to the presence of the ice sheets, their high reflectivity, and above all the resulting power of the MPHs. However, summer warming slowly reduced the ratio of snowfall in the precipitation, favouring the ice surface melting already around 20 ka. Then began the slow retreat The MPHs, still powerful, continued to capture and deviate polewards the increasing sensible and latent heat potential, and to provoke heavy rains They therefore strongly contributed to "the most rapid rate of change occurred between 14 ka BP and 12 ka BP" (Mix et al., 1985) After 11 ka, the insolation being at that time 9% higher than present at North Pole, melting of continental ice sheets accelerated (Denton et al., 1981; Duplessy et al., 1984; Nakada et al, 1988). In the same time, the progressive continental ice dissipation let Greenland merge as a relative relief and then modifies the starting point and the paths of MPHs in the Atlantic Ocean area (Fig. 6).

After 10 ka the Laurentian and Scandinavian ice sheets were considerably reduced The earth entered a warm circulation mode (Fig. 13), which fits the Holocene Climatic Optimum, roughly from 9 ka (to include the tropical zone where change was earlier) to 5 ka. "In the Arctic, the Climatic Optimum was attained roughly 5000 years ago" (Maxwell et al., 1989), in the middle latitudes it occurred around 6 ka, the summer temperatures being then higher from 2°C than present (Huntley et al, 1988). In Asia "the period 7500 to 5500 yr B P was the warmest and wettest... the annual mean temperature was 4°C warmer than present in the Tibet plateau, 3–4°C warmer in NE China, 2–3°C warmer in E China and N Japan, and only 2–2.5°C warmer in S Japan and Taiwan Island" (Tianchi, 1988) The paths of weakened MPHs displaced polewards, and for example, in the northwestern Pacific Ocean the "axis of maximum speed of the westerly circulation. . retreated northward during the Holocene to a poleward extreme at about 6000 years ago and then moved back toward the equator" (Rea et al, 1988).

The tropical zone, progressively enlarged, allowed a high freedom of displacement of airflows and discontinuities, and the migration amplitude of the Meteorological Equator and monsoons was then at its maximum (Kutzbach et al., 1982; Van Campo, 1986). Warming favoured the occurrence of deep thermal lows over tropical continents and large transequatorial pressure drifts amplified the Indian and African monsoons. Northwest India was then "warm-humid with frequent floods" (Pant et al., 1987), the western Arabian Sea and the Horn of Africa were concerned by "strong monsoons from SW", in boreal summer (Prell et al., 1986). At the same time, in austral summer, the SE trade was replaced by the Malagasy monsoon in the Mozambique Channel (Elmoutaki et al., 1992) In Africa the climatic zones were both displaced northwards and southwards (Van Zinderen Bakker, 1980, Kadomura, 1982), the Saharan hyperarid area then observed its major reduction, with an extension of the Sahelian zone up to 23°N, already at about 8 ka (Pachur et al., 1988, Fabre et al, 1988; Lézine, 1989; Leroux, 1991b), heavy rains and weakening of dry continental trades allowed, as in Amazonia, the evergreen forest maximum reconquest (Leroux, 1990b) and even its spreading far beyond its present limits (Hamilton, 1976)

Since the Holocene Climatic Optimum, and more precisely since 4.5 ka, the general circulation has remained in a slow mode, but sliding very gradually towards a rapid mode, due to insolation decrease in high latitudes (Fig 17), and the associated progressive increasing power of the MPHs.

Conclusion

The concept of "Mobile Polar High" (MPH) explains:

– the weather, its distinctive features, and its evolution from day to day, directly in middle latitudes, and indirectly in the tropical zone as far as the Meteorological Equator,

– the present climatic patterns, for example the very different climatic characteristics of regions located at about the same latitude, for example New England/or China–Japan (located near the starting point of cold MPHs), and Portu-

gal/or California (which receive warmed and weakened MPHs);

– the present climatic changes, for example the relation between the Atlantic Arctic temperature decrease since the years 1930–1940 (Rogers, 1989), and the geographical distribution of the negative anomalies of temperature in the North Pacific and the North Atlantic Oceans, as revealed by the sea and air temperature maps proposed by Folland et al. (1990) or/and Jones et al (1991), in fact along the MPHs paths (Leroux, 1992),

– and the past climates, as demonstrated above

The polar latitudes appear as the key control of the earth climate, in the past as in the present: they observe the highest variations of insolation, they store the captured water potential, they give the MPHs their initial power, and thus they govern the intensity of the general circulation, at the seasonal scale as at the palaeoclimatic scale

The MPH concept, founded on the real observation of meteorological phenomena, offers a coherent and comprehensive explanation, on all space and time scales, from local weather to the general circulation, from the present climatic features to the global past climates. It appears therefore impossible to remain ignorant of the actual importance of the Mobile Polar High still, the key factor of climate and of its evolution.

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