8

The general circulation of the atmosphere

This theory had radically changed our vision of the Earth, and, more than this, our way of practising geology, to such an extent that its emergence gave rise to bitter and acrimonious scientific debates, often too heated ...

The more novel an idea is, the more its power to shock, and the more it upsets those whose reputations have been established elsewhere, and those whose intellectual comfort has been troubled by its emergence. Originality is a prized virtue, provided that it is not too disturbing. Beyond a certain threshold, any bold innovation will be met with marginalisation, or even sacrificial reaction.

Claude Allègre. *Histoires de Terre*, Fayard, Paris, 2001.

Fedorov stated the fundamental principle in 1979 during the First World Climate Conference in Geneva: '*Variations in the climate are the effect of changes in the general circulation of the atmosphere, and also, no doubt, in the general circulation of the oceans*'. Later, the Intergovernmental Panel on Climate Change (IPCC) declared: '*Climate is determined by atmospheric circulation and by its interactions with the large-scale ocean currents and the land with its features*' (in IPCC, 2001, *Glossary*). Everyone, a priori, agrees on this point: the general circulation of the atmosphere is considered to be the vehicle for climatic variations, and all known (and predicted) variations are supposed to be analysed particularly by models within the framework of general circulation.

8.1 CLIMATE IS DETERMINED BY ATMOSPHERIC CIRCULATION

This means (or should mean) that climatology is (or should be) already in possession of a coherent schema of the general circulation of the atmosphere, applicable on all spatial and temporal scales. That schema explains (or should explain) how the 'atmospheric system' works, why and how it changes, and how the climatic consequences of previously established causes are transmitted through the links of general circulation. Also, such a schema must (or ought to) enable us to put each element into its correct place in the logical chain of phenomena, since each element, individually identified, is necessarily involved in the *ensemble* of mechanisms through links of causality. Logically, this is the way things *should* be, but is it the way they are?

Our thoughts turn immediately to models (cf. Chapter 7), and more especially to 3-D numerical models, more specifically known as General Circulation Models (GCMs). Are they really an indispensable tool? **The answer, unfortunately, is no**. In the words of Lindzen, '*models do not begin with a scheme of the general circulation; the general circulation is supposed to emerge as part of the solution*' (pers. commun., 12 January 2004). So the circulation is 'supposed to emerge'. It is not even a certainty! Surprising, but there it is.

8.1.1 Absence of a general schema

So, to use a concrete image, the climatic model is like a huge building site from which some future (and hypothetical) structure will arise: all manner of building materials, great and small, have been sorted and laid out in countless little piles on different parts of the site (the basic cells), but there is no general plan about this, no attempt to relate any element to any others. Each pile on the grid is seen only in the context of its neighbours: it is like an enormous 'Lego' kit with no user instructions. The architect can see no further than the basic cell, and cannot know what final form the building (the model) will take. The general layout and logic of the architectural whole will emerge by themselves (it is supposed), from the equations linking the basic cells. The only framework is that suggested by the points on the grid, but how each point, or set of points, relates to the whole is unspecified.

This shows the pointlessness of interrogating such a model as to how meteorological phenomena are governed by some initial cause (unless it can be defined previously), since the main thrusts and chains of activity are not identified.

What is more, without a general, coherent schema, it is impossible to appreciate the real importance of any one element in the context of the whole, and allot it its exact place in the unravelling processes. To take another image, let us compare this climatological reasoning with the assumption that, in the case of a car, the component (out of a multitude of possibilities) that makes the vehicle move is the radiator fan (!). This fan, which immediately suggests itself as the equivalent of an aircraft propeller or a ship's screw, is situated at the front of the car (rather like the propeller). When it is not rotating, the engine is not running; if the car accelerates, it moves faster. It seems to have all the properties of a 'factor', and might easily be mistaken for the 'engine' itself ...

But this is approaching the problem from the wrong direction. We can describe the fan (its colour, diameter, the width of its blades, what it is made of, etc.) as accurately as possible. We can observe and analyse, to a high degree of accuracy, what it does (direction of rotation, speed, ratio of its turns to those of the wheels, or to the speed of the vehicle), considering the multiple co-variations and statistical correlations involved. But this will still not reveal the cause of its motion, even though the existence of the fan belt might suggest a possible cause of the observed effect. Even then, only our knowledge of the way in which everything works will confirm that the fan has no part to play in the vehicle's actual motion, but belongs at the end (not at the start) of a chain of events and is but a minor consequence of it. The engine will continue to run even if the fan is disconnected. Our approach may be crude and erroneous, but it is made possible, as in many other cases, by the absence of a general schema in which the true place and function of the fan are made clear.

Unfortunately, climatology uses similarly futile reasoning when it suggests, for example, that:

- droughts, heatwaves, floods, and extreme meteorological events are the 'results' of the greenhouse effect, though no causal links have been established;
- the Sahel drought, or the 'Dust Bowl', are caused by temperature changes in the oceans, though the root cause of the changes is neither known nor investigated; and
- El Niño is a kind of *deus ex machina* causing numerous, totally different events worldwide, though its real nature and exact place in the chain of events are not known: it is only a consequence (like the motion of the car's fan) further along the chain. We shall come back to this later in Chapter 13.

How has such a situation come about? Dady (2001) underlined that the advent of modelling had spelt the end of working with concepts 'beyond the particle', in an effort to 'understand atmospheric evolution'. Ever since, for 50 years, climatology has been in a real conceptual *impasse* as far as general circulation is concerned. What is the first cause in the workings of general circulation? What are the causes of its variations, its structure and components, its modalities and organisation? What is the precise place of perturbations and their integration into the general dynamic? Where do the processes transmitting climatic modifications belong, whatever their timescale? What is the state of the debate on these questions, and many others? We need first of all to look back at past efforts to construct a complete and coherent image of atmosphere general circulation.

8.2 A BRIEF HISTORY OF THE CONCEPTS OF GENERAL CIRCULATION

Since the beginnings of meteorology, a description of general circulation has been sought, but this fundamental aim remains to be achieved. Let us examine the principal efforts.

The great voyages of the 15th century led to a progressive description of the 'Brave West Winds' of temperate latitudes, which brought Columbus back from America, and the tropical trades and monsoons. The first chart of winds by Halley in 1686, showing the trades between 30°N and 30°S, was used to elaborate the first theory of the dynamics of wind: the so-called 'equatorial chimney'. The first theory of general circulation saw Hadley (1735) assert the primacy of tropical heating: warm air rose at the equator, streamed at altitude towards the poles and returned to the tropics via the lower layers, drawn in by the relative vacuum of the 'chimney': general circulation comprised two convection cells, one in each hemisphere. Hadley claimed that the direction in which the trades blew was the result of the difference in the speeds of rotation of the equator and the poles: air coming from the pole is slowed by the Earth's surface, which moves fastest at the equator, and therefore seems to come from the east. By the same reasoning, air moving towards the pole travels eastward faster than the Earth's surface, whence the existence of westerly winds in mid-latitudes.

8.2.1 Birth of the tri-cellular model of circulation

A century later, in 1835, the mathematician Coriolis showed that the trajectory of any object moving across a rotating body will describe a curve at all points on that body's surface, independently of the starting point and of the direction of the object, once set in motion. The oceanographer Maury carefully collated from ships' logs a considerable amount of documentation concerning sea and air currents, and revealed the existence, previously unsuspected, of zones where mean atmospheric pressure remained relatively constant: low-pressure zones near the equator and the poles, and high-pressure zones at about 30° north and south. In 1855 he put forward a plan of general circulation incorporating these pressure zones, with two cells in each hemisphere, and air rising at the equator and subsiding at 30° in each hemisphere (already the 'Hadley cells'). But he also showed a current from the tropics to the poles in the lower layers, rising at the poles, which were calmer zones, like the equator.

Ferrel, a teacher, drew upon the principle set out by Coriolis and the observations of Maury, and in 1856 proposed a schema of general circulation marshalled by the geostrophic force, based on three circuits. This tri-cellular model would influence meteorology for a long time to come. In the subtropical (now 'Hadley') cell, equatorial air rises, then descends at about 30°N and 30°S to return to the equator. However, all the air does not return towards the equator: some travels towards the poles at low level, but at about latitude 60° it encounters cold air leaving the poles, and rises, moving back in upper levels towards 30° and falling again. This forms the second circulatory cell (later known as the Ferrel cell). The third cell is the polar one: cold air moves away from the pole, warms up, and at about latitude 60° it rises and returns towards the pole. Notice that, at the extremity of the temperate cell, we have a meeting of 'warm' air from the south and 'cold' air from the north: cold air which, in the polar cell, is nevertheless capable of rising on its journey back to the pole!

Ferrel's tri-cellular schema gave (provisional) answers to questions of the day, such as that of the existence of the equatorial calms feared by sailors, at the junction of two tropical cells. Subsidence of the air at latitudes 30°N and 30°S, with high-pressure belts, explained the great continental deserts and the oceanic tropical calms known as the 'horse latitudes'. At polar latitudes, the Coriolis effect caused prevailing easterlies, and for the same reason the equatorial (trade) winds were westerlies.

The convergence, at about 60°, of polar air and warm air from the temperate zones formed the great depressions and anticyclones of middle latitudes.

Ferrel's model was hailed in his day as a great breakthrough, and the call of the tri-cellular model of circulation still echoes loudly in today's meteorology. However, it has its shortcomings, and many people have tried to improve upon it. For example, Thomson's schema of 1857 caused Ferrel to modify his own in 1889. The cells became far less individualised, and the polar easterlies disappeared, to be replaced by the 'polar calm', but the 'tropical calms and dry belt' and the 'doldrums and equatorial rain' were retained.

8.2.2 Improvements of the tri-cellular model of circulation

The end of the 19th century saw the advent of new representations from Guldeberg-Mohn (1875) and von Helmholtz (1888), a forerunner of the Bergen school, who laid down the principle of the conservation of energy and the vortex theorems. In the early 20th century there were further contributions from Margules (1903), Hasselberg-Sverdrup (1914), Ekner (1917), I. Bjerknes (1923), Bergeron (1928), Dedebant and Wehrle (1933), and Rossby (1941) (in Olcina and Cantos, 1997). Margules described the structure of a discontinuity within a fluid in rotation (i.e., a front). J. Bjerknes (1923) kept the trade wind, the counter-trade, and subtropical subsidence, but between latitude 30° and the pole he introduced the Polar Front, with families of perturbations and sporadic winter irruptions of polar air into lower latitudes (foreshadowing Mobile Polar Highs, MPHs). Dedebant and Wehrle (1933) expounded the theory of differentiated rotation: briefly put, the atmosphere does not move *en bloc* like the Earth, but is separated into rings of different velocities as a function of latitude and altitude, with easterly winds in the equatorial ring and westerlies in the polar rings, where their speed increases up to the tropopause.

Rossby, another member of the Bergen school, did not follow Bjerknes' schema, and, like Bergeron (1928), he proposed a tri-cellular circulation model (1941) with general circulation explained through combinations and adjustments of forces, the dynamical factor taking precedence over the thermal factor. The success of this model owed much to the status of Rossby, who had been in the USA since 1926 and had founded the Meteorology Department at the Massachusetts Institute of Technology (MIT). In its main features, this model is actually quite close to that of Ferrel, with three cells in each hemisphere: the Hadley cell, the Ferrel (with exchanges between these two cells) and the polar; a new feature was the Polar Front, a continuous separation between polar air and air flowing from subtropical high-pressure areas of essentially dynamical origin. The Ferrel cell, also essentially dynamical, is supplied with energy mobilised by enormous Norwegian 'cyclones'. This model does not include jets, but in 1947 Rossby overturned concepts when he stated that the origin of temperate-latitude perturbations (the Polar Front) lay in the high-altitude jet stream.

In 1921, Defant had explained that exchanges took place in steps rather than in a continuous current from the pole towards the equator, and that these exchanges were mechanical and carried out within large-scale perturbations (anticyclones and moving lows), which create widespread turbulence. The progress of families of cyclones brought about step-by-step meridional exchanges. Palmen (1951) took up this idea, and attempted to reconcile matters: he considered the polar zone to be a zone of mixing, and he introduced jets and connected the temperate and tropical cells. During the 1950s, Ferrel's model was judged to be unrealistic by the meteorological community, as it contradicted observations. Since then, Palmen's model (which nevertheless owes much to Ferrel's), with later slight modifications (Palmen and Newton, 1969), is considered to be the best elaborated of the schemas of general circulation.

Modelling has not brought further decisive progress in the interpretation of general circulation. Phillips' attempt in 1956 at simulation of the movement of the atmosphere in one hemisphere, in response to the controversies of 1940–1950, did not produce the desired results. Lewis (1998) commented: '*The experimental design was bold*', but '*the simplicity of the model dynamics exhibited an almost irreverent disregard for the complexity of the real atmosphere*'.

It must be pointed out that, without special instructions, models based on radiation can only deal with the more or less direct consequences of temperature differences (on pressure gradients or circulation) from cell to cell. So they can only describe a unicellular circulation in each hemisphere, from the pole towards the equator in the lower layers, and in the opposite direction at altitude, in fact reproducing Hadley's initial 'equatorial chimney' schema of 1735.

Representations of general circulation therefore remained at a certain point, and for about 50 years Ferrel's tri-cellular model (1856), as revised by Rossby (1941) and Palmen (1951, 1969) has been the preferred doctrine. Although this model is now seen as '*a vast oversimplification*', it still provides a useful conceptual tool (Henderson-Sellers and Robinson, 1989). In France, it continues to be reproduced and taught, especially in universities (cf. Beltrando and Chémery, 1995). Météo-France, the French Meteorological Society (SMF) and the Laboratoire de Météorologie Dynamique (LMD) still consider that the general circulation of the atmosphere comprises '*three meridional cells in each hemisphere, from the equator to each pole. These are the Hadley cell, by far the largest and most active, the Ferrel cell and the Polar cell*' (De Félice, 1999, cf. site `www.smf`).

8.3 INSUFFICIENCIES IN THE REPRESENTATION OF CIRCULATION

Although Ferrel's legacy has been amended, it does not even approach an explanation of the true nature of meridional exchanges. The principal shortcomings are as follows:

- In the Polar cell (direct sense) 'warm' air rises and cold air 'falls', conforming to thermodynamics. But it is difficult to understand how air flowing from the pole might have been 'warmed' on reaching latitude 60°, and be warm enough to rise and return to the pole! This Polar cell is improbable. Also, *polar easterly winds* are not observed. What is more, if this happened, it would never be cold outside the polar regions! We know that this cell has been re-named, but to call it now a 'mixing zone' does not tell us much more about the nature of meridional exchanges.

- In the temperate or Ferrel cell (indirect sense) the air which is moving back towards higher latitudes is progressively cooled, but it still rises at around 60° latitude! It is supposed that the movement is brought about by the other cells: a rather simplistic viewpoint. This cell, which works contrary to physical principles, is also therefore quite improbable!
- In the Hadley cell (direct sense) equatorial updrafts are certainly observed, but the subsident aspect (which is supposed to create deserts) does not involve the surface, because at the latitude where subsident movements happen, we find not only the Sahara, but also the West Indies and the Yucatán!
- The tri-cellular schema segments the exchanges and thereby does not envisage long-distance transfers, nor can it explain waves of heat and cold; also, it does not allow for thermal equilibrium in the Earth–atmosphere system. The 'cellular' concept might well have been credible in the days when distances seemed so great and zones so well separated, when tropical weather was 'independent' and red rains across Europe were known as 'rains of blood' ... though nowadays we all know that the red dust comes from the Sahara, just as those living around the Gulf of Mexico know that the *nortes*, like the winter rains of the Cape Verde Islands, are of far-away 'polar' origin!

Ferrel's schema and those that followed it were based on observations: initially those of Maury, and mainly of the mean pressure field:

- with low pressure corresponding to convergence and upward movement; and
- with high pressure corresponding to divergence and downward movement.

With these principles in mind, it was easy to imagine the three cells; but these schemas established 'truths', often still considered to be incontestable postulates. For example:

- The meteorological equator (ME), axis of the so-called 'equatorial' lows, is a location of updrafts, a notion implied within the generic term 'Intertropical Convergence Zone' (ITCZ). This is not always true, especially in the case of the inclined meteorological equator (IME), which is not necessarily characterised by vertically ascending air.
- Anticyclonic areas are created by air descending through the whole depth of the troposphere. Chen *et al.* (2001) mention the ambiguities which surround this idea: '*The low-level tropical anticyclones in particular continue to be an open question*'. So '*tropical high-pressure areas*' (e.g., the 'Azores' or 'Hawaiian' anticyclones), defined using mean pressures, are generally considered to be 'permanent centres of action'. This way of thinking has caused an incredible **confusion of scales**. **A 'centre of action', defined using mean pressures (i.e., statistically), has no real existence on the scale of real (synoptic) weather**. This

confusion is still very much alive, and falsifies the perception of phenomena, masking the real origin of these anticyclonic cells.

The representativeness of mean wind values does not have the same meaning in the tropical zone and in the extra-tropical zones:

- in the tropics, mean values are representative of the real wind field (i.e., with the direction of the synoptic wind deviating very little from the vector of the mean resultant wind); and
- outside the tropics, the continual passage of MPHs causes the wind constantly to change its direction completely, so the 'mean direction' of the wind has no real synoptic meaning.

Therefore it is impossible to represent tropical and extra-tropical circulations in the same way in a schema of general circulation (which necessarily deals with means): any streamlines shown will be representative of reality only in the case of tropical winds.

Let us also mention that perturbations, and especially those of middle latitudes, are not integrated into the dynamic of circulation. For example, '*the most significant feature of the general circulation of the atmosphere in temperate latitudes is the existence of prevailing westerly winds. Superimposed upon these are perturbations which can mask the dominant character of these winds*' (Rochas and Javelle, 1993): meaning that perturbations in temperate areas, appearing *ex nihilo*, are not integrated into the westerly flow, and 'graft' themselves onto the circulation without really becoming an integral part of it even if they are moving in the same direction!

As a consequence of these preceding points, meteorology, and therefore models, do not really possess a coherent picture of general circulation. To a non-climatologist, this might seem unbelievable, but it is a fact that cannot be ignored, if we are discussing the prediction of climatic changes; because **no parameter, and no climatic region, can evolve independently,** since everything is more or less closely connected!

8.4 THE CONCEPT OF THE MOBILE POLAR HIGH

The first time that the necessity for a new conception of general circulation came to me was during research into tropical meteorology. For example: observations of variations in temperature, pressure, and the speed of the trade wind showed that subsident air was quite incapable of instigating the rapid accelerations and sudden cooling in that flux. The preparation of 250 mean meteorological charts at different levels for tropical Africa and the description of the vertical structure of the troposphere (Leroux, 1983) showed equally that the troposphere over the tropics is not homogeneous, but highly stratified, with distinct horizontal discontinuities such as the Trade Inversion (TI) and the IME. It seemed moreover that the tropical dynamic was closely associated with the extra-tropical, represented by MPHs arriving at

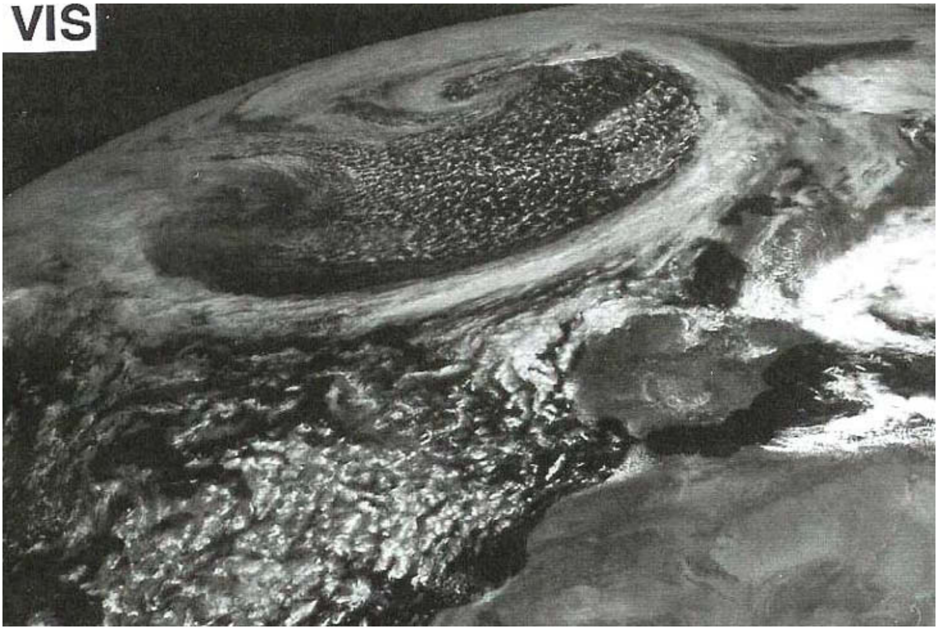


Figure 22. Cloud pattern connected with a typical MPH (28 April 1986, 12 h UT, Meteosat, visible). Cold Arctic air flows across the North Atlantic Ocean in the form of an MPH in the lower levels off the southern part of Greenland. On the leading edge of the MPH, a warm cyclonic air flow carries the subtropical water potential toward high latitudes and especially toward Greenland. A previous MPH now supplies the Atlantic trade flow, blowing southward off the coasts of the Iberian Peninsula and West Africa.

tropical margins and feeding trade wind circulation, and thereafter monsoon circulation, in the lower layers (Figures 22 and 23).

It was then necessary, by tracing the MPHs back to their source, to make a day-by-day analysis, using synoptic charts and satellite images, of the appearance, motion, transformation, and (supposed) 'disappearance' at the edge of the tropics of the 'motors' of circulation, the constantly renewed MPHs. A manual count for the whole of the northern hemisphere based on the *European Meteorological Bulletin* served chiefly to establish the trajectories and frequencies of MPHs for the period 1989–1993 (Guimard, Mollica, Moreau, de La Chapelle, and Reynaud of LCRE). Additional regular computer-based analysis has been done by Favre (for the North Pacific) and Pommier (North Atlantic), as part of their theses at the Climatology Laboratory (LCRE), Lyon.

8.4.1 Characters and structure of MPHs

MPHs (Leroux, 1983, 1986, 1996a, 2000) are in the main directly and visibly responsible for variations in pressure, wind speed and direction, temperature,

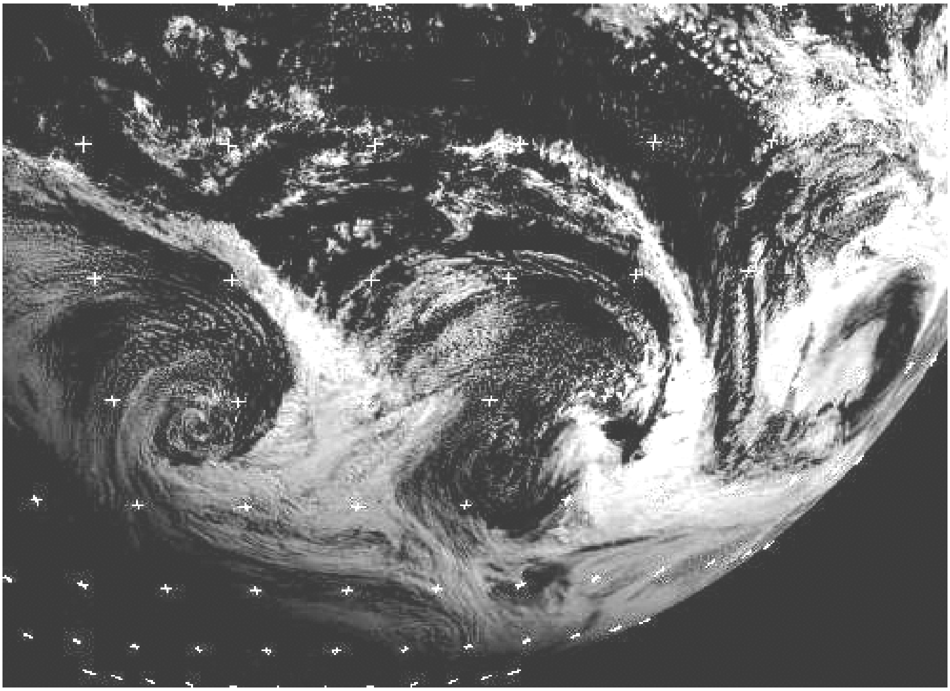


Figure 23. 8 July 2004, Goes 10, 18 h UT, visible. Five MPHs, separated by bands of clouds, are present on this picture of the south-eastern Pacific Ocean. On the right-hand side, an MPH has reached the South American relief (visible on the extreme right) and supplies the Easter Anticyclonic Agglutination and the maritime trade. South of this first MPH, another is rushing down from Antarctica. In the centre of the picture, one whole MPH is well outlined by interior anticyclonic rotation and by the cyclonic circulation around it; however, its north-western part is already opened to feed a maritime trade flow blowing north-westward. On the left-hand side of the picture, one (partly visible) MPH is followed on its southern side by another one rushing from Antarctica.

humidity, and cloud and rain amounts in extra-tropical areas – they are indirectly, and to a lesser extent, responsible for them in tropical areas. They are therefore responsible for the perpetual variations in the weather, and for the variability of the climate, on all timescales.

The thermal deficit which is ever-present at high latitudes, and at its greatest in winter, is responsible for the cooling and subsidence of the air above the Arctic/Greenland and Antarctica. As the descending air falls into step with the Earth's rotation, it will reach a critical mass and detach itself, rather like a drop of water, moving away from the pole in the lower layers as a *mobile lenticular body of dense air*, approximately 1,500 m deep and of the order of 2,000 to 3,000 km in diameter.

Figure 24, based on the *Meteosat* image from 26 April 1986 and the corresponding synoptic chart, shows in simplified form the association of surface wind and pressure fields in an MPH. In form, an MPH is a mobile combination of an anti-

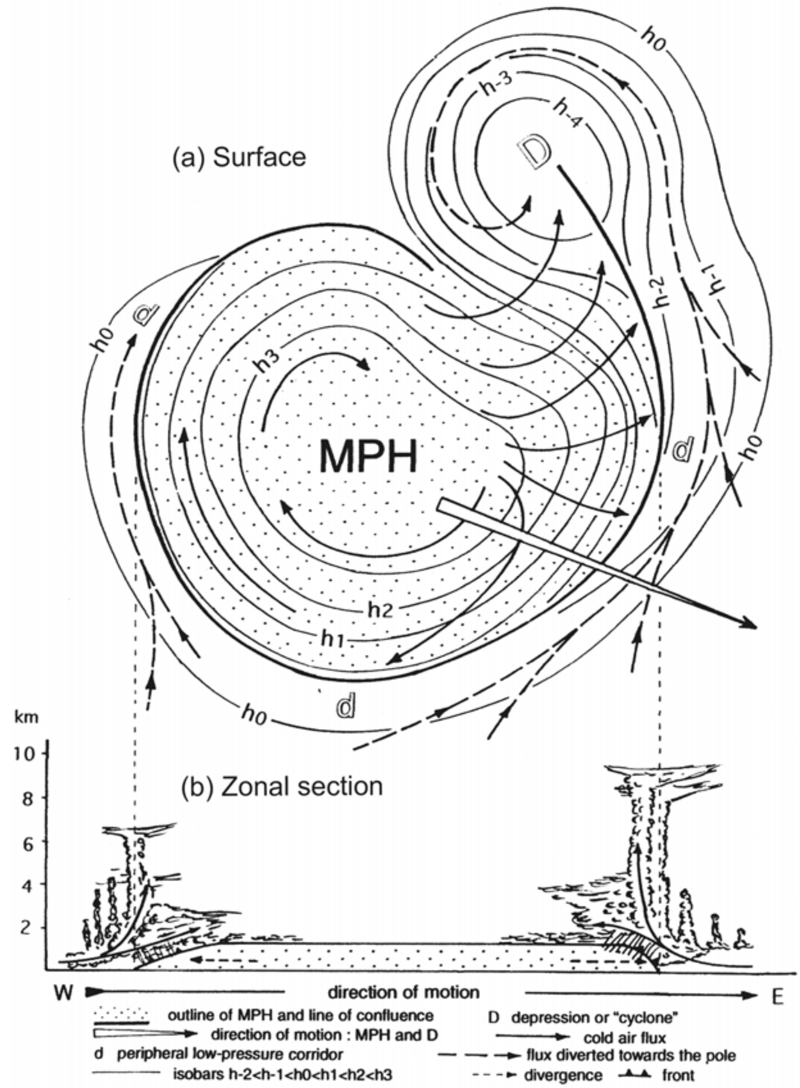


Figure 24. An MPH: (a) northern hemisphere surface pressure and wind fields; (b) vertical structure of an MPH and associated clouds.
From Leroux (1986, 2000).

cyclone (cold air: the MPH itself, the 'motor' of the whole unit), a peripheral low-pressure corridor, and a closed depression (of warm cyclonic air), both closely associated with the anticyclone and owing their existence and characteristics to it. The terms 'cold' and warm' as applied to air can have either an absolute or a relative value. The displacement *en masse* of an MPH cannot be related to the actual direction in which the wind blows: within the MPH it is anticyclonic, and in the peripheral low-pressure corridor and/or the closed depression, cyclonic.

The weather associated with MPHs in polar and temperate latitudes is a function of the respective densities of the air within the MPH, and the surrounding air. All the while the MPH's air remains cold, and therefore denser, the surrounding (relatively or absolutely) warm air will be lifted, and the MPH will be surrounded by more or less dense cloud formations (Figures 22 and 23). In winter, MPHs are more powerful and their trajectories more meridional, intensifying meridional exchanges and transfers of energy (especially perceptible heat and subtropical, or even tropical, latent heat). As a result, the peripheral low-pressure corridors and the closed depressions (cyclones) are deepened, updrafts (dynamical convection) are more vigorous, and the weather 'worsens', with increasingly frequent storms (cf. Chapter 11).

8.4.2 Trajectory and formation of Anticyclonic Agglutinations

The trajectory of MPHs from the poles towards tropical margins is determined by:

- The dynamic nature of the MPHs themselves, with generally NW to SE trajectories in the northern hemisphere and a more or less pronounced meridional component, moving closer to the tropics in winter as the MPHs' vigour and speed increases.
- Relief of more than 1,000 m (the approximate mean depth of MPHs), especially continuous mountain ranges. Relief channels some or all of the mass of the MPH, imposing trajectories and determining the units of circulation in the lower layers.

The gradual slowing of MPHs, the intersecting of their trajectories, and the effects of relief cause them to merge, and low-pressure corridors and cyclonic circulation between MPHs will diminish and disappear, with the formation of Anticyclonic Agglutinations or AAs (Figure 25). These AAs may become 'permanent' (mostly over oceans to the west of mountain ranges), they may be seasonal, or appear only in winter (and not only over land); or they may be occasional and of variable duration (cf. Chapter 11).

Trade wind circulation is born of these agglutinations of MPHs on tropical margins, which are veritable 'buffer zones' of general circulation within which anticyclonic rotation gradually asserts itself. The trades will possibly evolve as monsoons on crossing the geographical equator. Pulsations in the fluxes of trades and monsoons deflect the MPHs which are constantly arriving at the AA (Figure 25).

8.5 UNITS OF CIRCULATION IN THE LOWER LAYERS

The lower layers of the troposphere are of primary importance in climatology. They are the densest layers, and contain nearly all the water vapour and other greenhouse gases. Also, circulation in the lower layers is much more complex than that of the upper layers, because of:

- the Earth's surface warming the atmosphere;

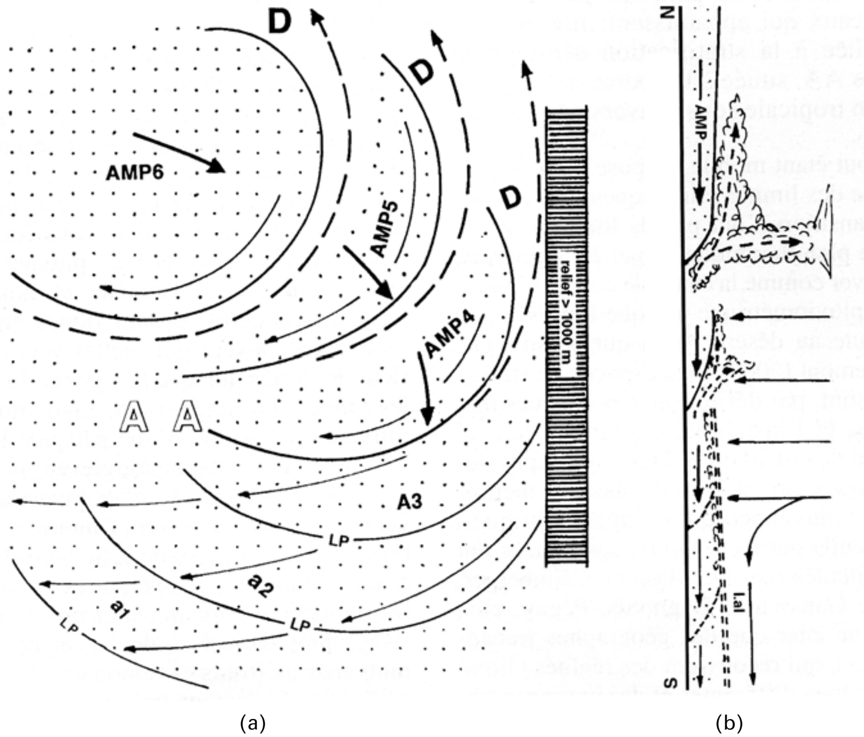


Figure 25. Formation of an AA, by merging of MPHs and birth of trades. (a) pressure and wind fields at the surface (a1, a2, a3: serial number of successive MPHs); (b) meridional vertical cross section corresponding to surface pattern (a) (AMP = MPH, LP = line of pulsation in the trade, I.al = trade inversion or TI).

- differences in the substratum;
- the thermal behaviour of oceans and land masses;
- vertical upward and downward movements caused by the surface (compression, turbulence, convection);
- thermal gradients arising from differential warming;
- effects of attraction caused by deep tropical thermal lows; and
- differences in altitude (especially the presence of high mountain masses).

Circulation in the lower layers is marshalled by MPHs, 'motors' of the general circulation, and by the geographical factor (namely mountain ranges). The permanent thermal deficit at the poles, and the resulting subsidence, cause a lenticular mass of cold air, initially about 1,500 m deep, to move off into the circulation at the rate of about one a day from either pole. As they travel and spread, these vast discs become shallower. Therefore, mountain chains of the order of 1,000 m high will present an almost insurmountable barrier to this cold air (though this is not the case with the warm cyclonic air associated with MPHs, which can cross such obstacles). Great mountain walls such as the Rockies and the Andes, or the line of

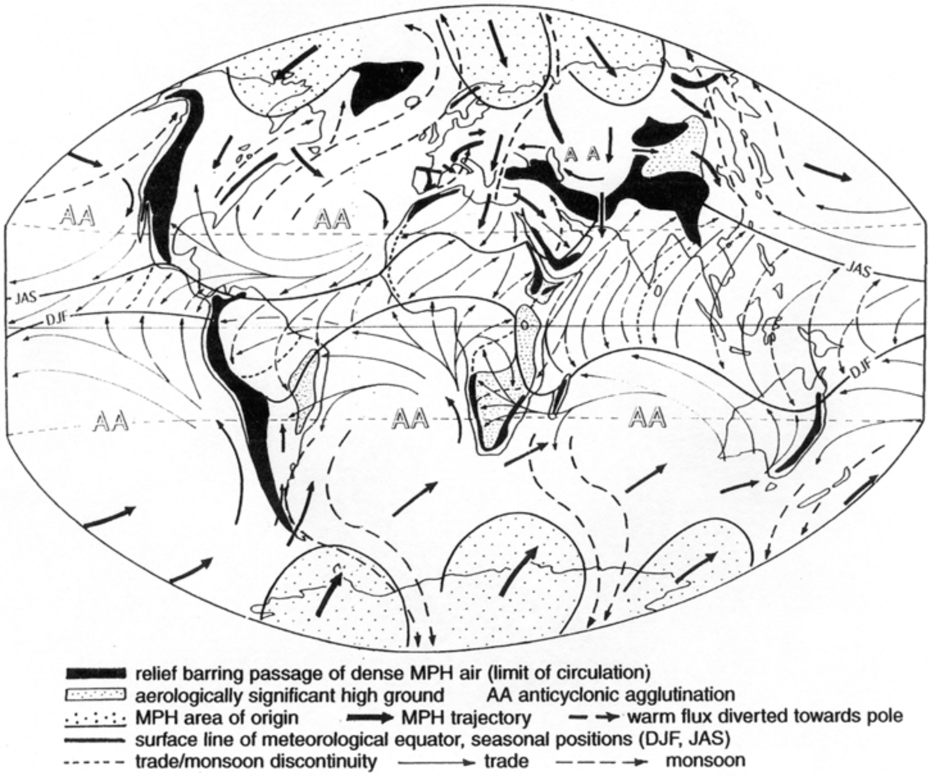


Figure 26. Circulation in the lower layers (diagrammatic), showing the six main aerological units determined by MPH dynamics and relief.
From Leroux (1996a).

highlands from the Pontus, the Caucasus, and the Zagros chain, right down into the Himalayas and Tibet, are absolute barriers to the dense air carried in MPHs, which are diverted in their entirety. Continuous mountain ranges, even if they are not quite as imposing as those already mentioned, cause the agglutination of MPHs, and by impeding the free passage of air, they determine the courses of vast units of circulation.

The vast spaces within which circulation occurs are fairly distinct, if extendable, and there may be 'traffic' to varying degrees between these spaces. Six aerological units are recognised, three in each hemisphere (Figure 26):

- North America/North Atlantic/western Europe;
- Northern and central Europe/Mediterranean/Middle East/northern Africa;
- East Asia/North Pacific/western North America;
- South America/South Atlantic/western and central Africa;
- Southern and eastern Africa/Indian Ocean/Australia; and
- Eastern Australia/South Pacific/western South America.

The dynamics of two of these spaces will be discussed in Chapters 12 and 13.

Each aerological unit of the lower layers has its origins at the pole, with relief intervening sooner or later to channel MPHs and lock them into their proper units of circulation. Within each unit, cold air advected by MPHs describes immense, elongated 'figures of eight', with air arriving from the pole and then travelling from west to east with a meridional component roughly down the middle of the unit. Next, an AA forms at the eastern edge, the trade circulation picking up tropical heat and water, and air returning to the pole by way of the cyclonic circulation on the leading edge of new MPHs. The latitudinal extent of each unit is limited by the surface line of the ME, their maximum extension occurring in winter when MPHs and their associated circulation are at their most vigorous.

In the oceans, circulation at the surface is controlled by the circulation of air (cf. Chapter 14). The driving force of marine circulation is yet again the MPH, which by pressure and its very size brings surface water eastwards in mid-latitudes, to more southerly latitudes in winter and more northerly latitudes in summer, in the northern hemisphere. The encounter with the land mass to the east of the unit, beneath the AA, divides marine circulation, with anticyclonic rotation drawing subtropical currents towards the equator. These currents store energy which will be sent back towards the temperate zone on the western edge of the great oceanic gyres thus created. This (slower) circulation effects in this way between 20–25% of the meridional heat exchanges. As a consequence, its intensity varies with that of the circulation of the air, and by extension, with the vigour of MPHs, more rapid in winter (or long-term cold periods) and slower in summer (or long-term warm periods).

8.5.1 Dynamical unicity and climatic diversity

In each unit of circulation spatial diversity is wide, and on the dynamic scale we can distinguish some very distinct regions:

- those from which cold air preferentially departs (i.e., near the pole (with little warm air advection from the south observed at the surface));
- those directly upon the trajectory of MPHs: regions which experience alternating circulation – cyclonic (ahead of MPHs) or anticyclonic (beneath MPHs), with western edges of units preferentially (on average) transferring cold air, while eastern edges experience intense updrafts of warm air;
- those away from the usual path of MPHs (i.e., in areas of associated depressions and warm cyclonic fluxes), though the passage of MPHs is not completely out of the question;
- those located beneath a remarkably stable AA, though this stability is only relative, since variations in strength and north–south migration are nevertheless observed; and
- those beneath a trade wind circulation extending the AA, possibly transformed as a monsoon. In this case, in the tropical zone, the eastern edge will exhibit both cool air and cool water, while the western edge is warm.

While some regions experience more or less constant conditions (especially if the influence of high mountain chains is felt), others show continual variations on a daily, seasonal or even interannual basis. For example, in the zone between the two extreme seasonal positions of the ME (Figure 26), the trades and the monsoon blow alternately. Other regions lie at the junction of two meteorological spaces. One of these is western Europe, which is influenced alternately by the Atlantic and the Eurasian units of circulation. The latter is responsible for very cold periods, especially in the winter.

In spite of the diversity of these geographically scattered units, **within each aerological space the initial dynamic is the same**, dictated to various degrees by the same MPHs, and so all the parameters of the unit are interdependent. Within the space, even if the logic of reactions seems to differ and climatic outcomes vary, there exists a **general co-variation** of climatic parameters. Another aerological space will have its own dynamic, organised by its own MPHs and the particular geographical conditions affecting its circulation. Interactions involving separate units in the same hemisphere may arise from communication between more or less compartmentalised units, or from the **conditions prevailing at the starting point of the circulation (i.e., at the pole concerned).**

8.5.2 The fundamental questions

The way in which circulation in the lower layers is organised calls into question many points which had been thought (and which are still thought by some) to be solidly established.

- The origin of the circulation does not lie in updrafts resulting from heat in the tropics, but is rather caused by the thermal deficit, and the variations in that deficit, over the polar regions. Because of this deficit, new ‘discs’ of cold air are constantly being injected into the circulation, with varying degrees of energy, thereby encouraging the return of warm air towards the poles.
- Circulation is not a continuous process (i.e., flowing step by step as in models), but is constantly renewed as cold, lenticular air masses (MPHs), transporting their inherent thermal characteristics (and others picked up along their paths), perturb the circulation of higher and middle latitudes. Then, calmed, they supply tropical fluxes. The arrival of these enormous volumes of ‘new’ air (or, more correctly, **recycled via the poles**), orchestrates the intensity of meridional exchanges, both warm and cold.
- The polar/temperate zone is not, strictly speaking, a ‘mixing zone’, but a zone of rapid meridional transfers, where the notion of ‘mean winds’ has no climatic meaning.
- Cyclonic circulation to the fore of MPHs effects an intense transfer of water vapour, and, consequently, of energy, most but not all of which originates in the tropics. The majority of the water vapour is transported in the lower layers (i.e., the lowest 1,500 m), as Peixoto and Oort (1983) underlined, remarking especially that ‘*the transport of water vapour is clearly influenced by topography*’.

- There is *no break in the circulation within each aerological space, and no interruption between temperate and tropical circulation*, from the pole to the ME, and therefore there are **no closed cells in the lower layers**.

Figure 27 is an expressive illustration of this continuity. It shows an encounter between an MPH and the Great Escarpment at the edge of southern Africa, on 1–7 August 1999. The MPH is slowed and divided by the relief, with most of the air it carries remaining in the South Atlantic, where an AA forms (statistically defined via mean pressures as the 'St. Helena anticyclone'). Now a trade wind, it is accelerated along the coast of Namibia along the base of the western escarpment, which, at a mean height of 1,500 m, remains above the cold air and prevents it from flowing onto the southern African plateau. The maritime TI generates low, thin, stratiform clouds. The air of the MPH spreads progressively northwards and westwards, crossing the Angolan highlands and entering the Congo basin. On 5–6 August, it crosses the geographical equator and assumes a monsoon trajectory (Atlantic monsoon) moving into western Africa on 7 August. Over the ocean, that part which is now the maritime trade nears the coast of Brazil on 6–7 August. At the base of the higher eastern escarpment (the Drakensberg range), the southern fraction of the MPH, now fairly small, reaches Natal on 3 August, and southern Madagascar on 5–6 August. Therefore, the cold air of the MPH moves onto the continent by way of the anticyclonic rotation, entering through the valleys of the Limpopo and the Zambesi, and supplying the continental trade, which flows westward across the plateau; and then, after crossing the Namibian escarpment over the Atlantic, above the TI topping the lower layer of the maritime trade. On 7 August, a new MPH has arrived off southern Africa. A long band of cloud, oriented NW–SE on its leading edge, is evidence of the transportation of warm air back towards the pole. This new MPH feeds the maritime trade in turn, and then the subsequent monsoon. So the intensity of tropical circulation is determined by the frequency and power of the MPHs (i.e., by the polar thermal deficit). This is a fundamental aspect of the tropical dynamic.

- There are definite hiatuses between different units of circulation, and in the lower layers within which most air moves. So there is actually no 'single' general circulation, but specific circulations integrated into general circulation. The notion of globality and the interdependence of all phenomena, as presented by the models, is a long way from being a fact.
- AAs, or 'subtropical highs' (Figure 25), are present in the lower layers, with no intervention from upper levels. Now, subsident air is still almost universally recognised as '*causing the presence of the great continental deserts of subtropical regions: in Africa, the Sahara to the north and the Kalahari to the south; in America, the Mexican desert and the Atacama; the Gobi in Asia* (sic!)*, and the Australian desert*'! (Fellous, 2003). This is wrong for a number of reasons, not least of which is that the air subsidence in question occurs only above AAs, and cannot therefore reach the ground!

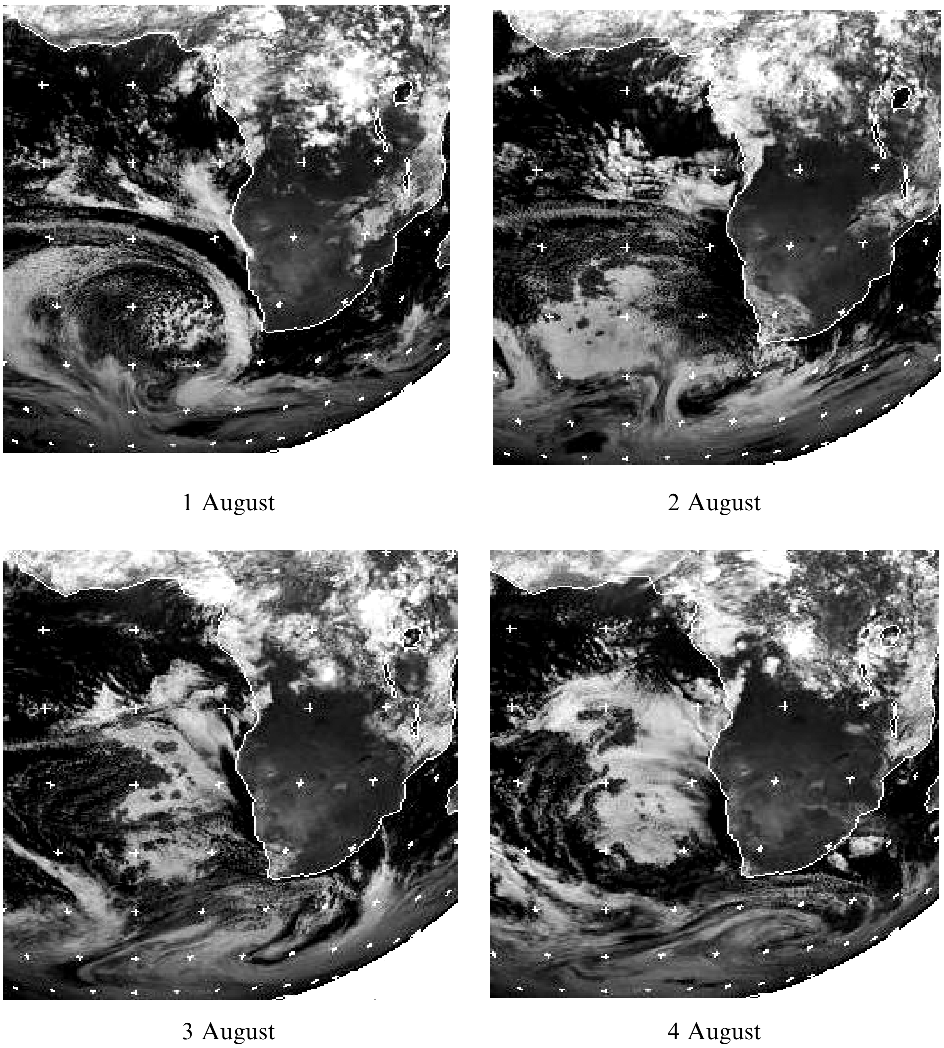
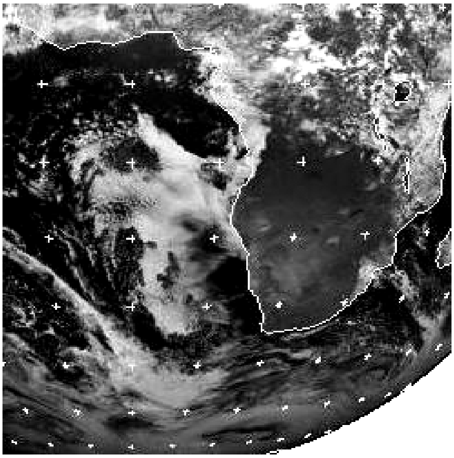
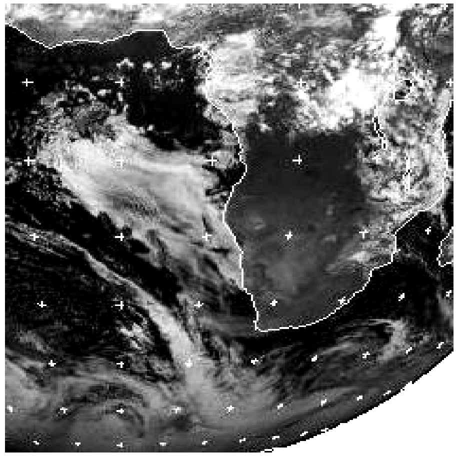


Figure 27. Supply of tropical circulation, trade, and monsoon by MPHs (1–7 August 1999, *Meteosat*, visible, 12 h, from Satmos–Eumetsat). Summary chart (SC) (path of the MPH's air from 31 July to 7 August): unbroken line – leading edge of MPH (or part of MPH); broken line (PL) – pulse line; GE – Great Escarpment around the highlands of Southern Africa.

- The geographical factor is normally not often taken into account, especially by models. Its importance is considerable as far as circulation is concerned, however, with relief being a main factor. For example, the Rockies, stretching from Alaska to southern Mexico, divide North America into two practically distinct units as far as cold air in the lower layers is concerned. Similarly, to the east of this barrier, water vapour is advected essentially from the Atlantic.



5 August



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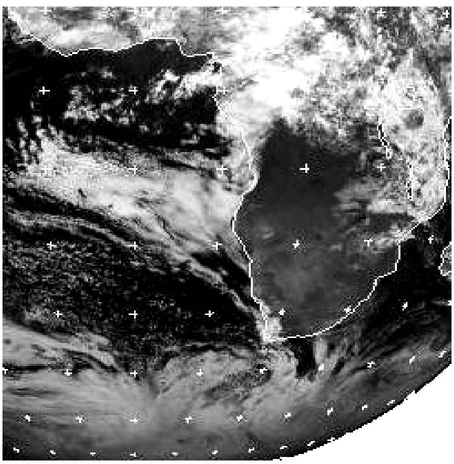

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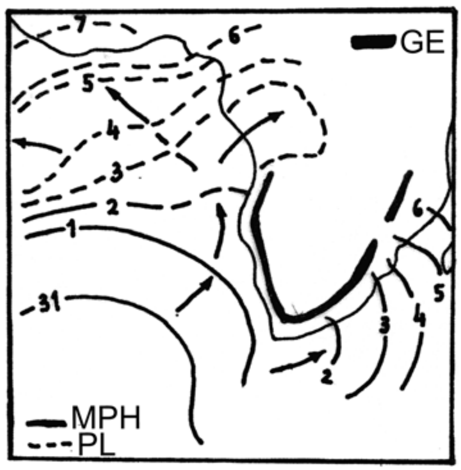

SC

The Andes do the same with the cold air and water vapour of South America. Again, the Himalayan–Tibetan mountains form a fundamental climatic boundary, denying MPHs access to the Indian subcontinent. The role played by relief is immediately obvious in the case of the high mountain chains, but more modest relief can also have a comparable effect. For example, the Great Escarpment around southern Africa, rising to about 1,500 m in the west along the Namibian coast, is able to split the flow of MPHs into both the Atlantic and Indian Oceans (Figure 27). Also, the mountains of the Iberian peninsula (Meseta, Sierras) force MPH air around them onto the western

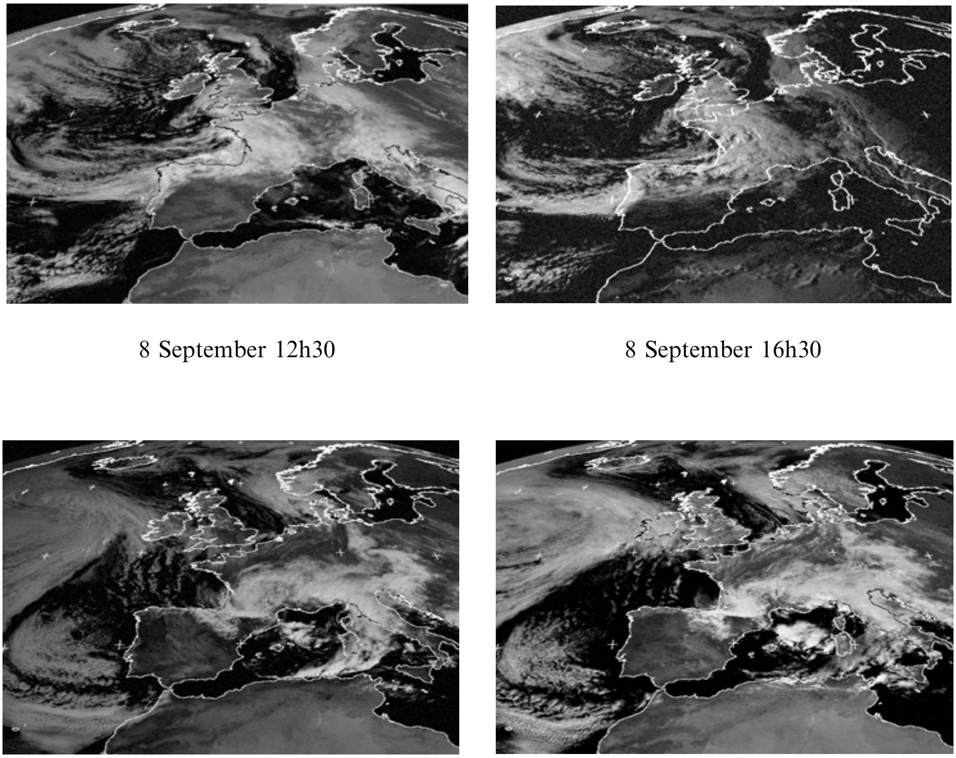

Figure 28. The influence of relief on lower level circulation (8–9 September 2003, *Meteosat*, visible). A large MPH moves across Western Europe. The east–west chain of the Cantabrian Mountains and the Pyrenees halts the cold air over the Bay of Biscay and the Aquitaine Basin. The leading edge of the MPH runs southward along the western side of the Iberian Peninsula, and eastward to reach the Mediterranean through the orographic funnel between the Pyrenees and the Alps. During the night of 8–9 September and the morning of 9 September, the MPH has passed along the northern side of the Alps toward Central Europe, and has passed round the Meseta high plateau and the Iberian Sierras. It invades the western Mediterranean area, following three paths: one through the French funnel (as *tramontane* and *mistral*), another (less intense) through Catalonia, between the Pyrenees and Celtiberian Sierra (*cierzo*), and the last (but not the least) between the Sierra Nevada and the Atlas. The Atlas range is itself impassable to the cold air of the MPH as far as Tunisia and the Gulf of Gabes. The MPH now supplies, on the western side of the Atlas, the Atlantic maritime trade, and on the eastern side of the Atlas, the Saharan continental trade (which will become the *harmattan* over western Africa).

Mediterranean, and the Atlas Mountains, extending E–W, prevent MPHs from directly penetrating North Africa west of Tunisia (Figure 28). The climatic consequences of these particular configurations are in the final analysis very significant (Chapter 11).

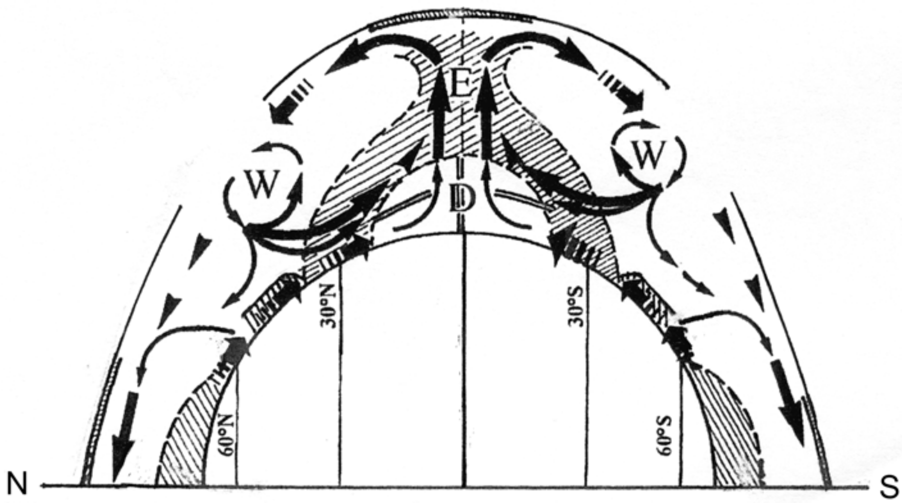

Figure 29. Troposphere: mean general circulation. Météo-France has adopted this scheme of general circulation, which has been taught at the French National School of Meteorology since 1992 (cf. Bonnissent, 1992), and published in *Météorologie Générale et Maritime,* Cours et Manuels No. 14, figure 9.7, p. 83 (Ecole Nationale de la Météorologie, Météo-France, Toulouse, 2001).
From Leroux (1983, caption: see figure 30).

8.6 GENERAL CIRCULATION IN THE TROPOSPHERE

The complexity of circulation in the lower layers is the result of the interference between the geographical factor (and particularly its orographical aspect) and the thermal factor, which causes the formation of the disc-shaped MPHs and of tropical thermal lows over continents. The influence of these factors is necessarily attenuated and finally negated at altitude. Then circulation becomes simpler, while the air becomes less dense. Eventually, only the major zonal currents remain, extra-tropical westerlies and tropical easterlies, concentrated into jets at about the altitude of the tropopause (Figure 29).

The starting point for circulation is at the poles, where MPHs form. The polar thermal deficit thereby provides the driving force for general circulation.

As MPHs move through the middle latitudes, they create, in the manner of a snow plough, two important displacements, horizontal and vertical:

- The diversion of warm air back towards the poles (Figure 24(a)) in the lower layers on the leading edge of the MPHs, and above them. This returning air will supply future MPHs.
- The lifting of warm air on the leading edge of MPHs (front and closed depression), and the liberation of latent energy (Figure 24(b)).

In those latitudes where intense vertical transfers of air take place, we also observe accelerations in the westerly (jet) circulation. These accelerations are strongest in

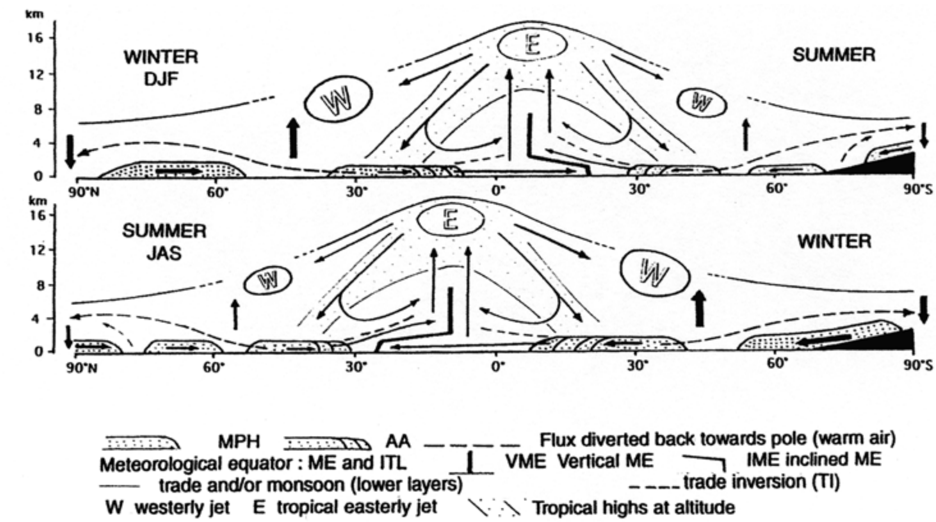

Figure 30. General circulation in the troposphere (vertical sections) according to seasons. From Leroux (1983, 1996a).

winter and weakest in summer as the power of MPHs and the intensity of updrafts vary. They are shifted nearer to the tropics in winter than in summer, because of the difference in the latitude reached by MPHs (Figure 30). The jets are consequences of lower layer phenomena, and especially of considerable vertical updrafts of air and energy caused by MPHs (and not vice versa).

AAs, formed by MPHs, are found only in the lower layers. From them springs the trade circulation, or more properly, the lower stratum of the trade, originally (within the AA) of the order of 1,000 m deep. The lower stratum of the trade becomes progressively warmer, and slowly spreads and deepens, becoming laden with water vapour. It meets the trade or the resulting monsoon (Figure 30) coming from the opposing hemisphere, along the ME.

Along the ME, updrafts, with deep convection, become general (Figure 29), for thermal but especially dynamic reasons, connected with the confluence/convergence of the circulatory hemispheres, impelled initially from the poles (cf. Figure 27).

The upward movement of air at the heart of the tropical zone has two major consequences:

- It supplies the Tropical Easterly Jet (TEJ), the vigour of which varies with the intensity of the updraft.
- It raises pressure at higher levels, forming Tropical High Pressure areas (THPs) which enclose the tropical zone in an inverted 'V' configuration (Leroux, 1983). These highs drive circulation in the direction of the poles, but the geostrophic force will not permit meridional exchanges across such a distance. Obeying mechanical laws, air at higher levels is rapidly drawn down towards the

surface, the descents tending to close off the Hadley cells at around latitudes 30° north and south.

The downward movements do not however reach the surface, as the lower layers are already occupied by the AAs and/or the lower stratum of the trade wind issuing from these same AAs (Figure 25(b)). A fundamental discontinuity is thereby created, between, on the one hand, subsident warm, dry air above and, on the other hand, the AA, or the lower stratum of the trade wind below, as it warms, spreads and possibly gains moisture. This discontinuity is the **Trade Inversion (TI)**, the climatic consequences of which are essential within the tropical zone as it is a horizontal, unproductive discontinuity (i.e., discouraging the vertical development of cloud formations). This is also the case in extra-tropical zones, as this discontinuity firmly dictates how water vapour is utilised, hindering its upward dispersion and concentrating it in the lower stratum of the trade.

Then, the remaining subsident (Hadley cell) fluxes may take two possible directions, one back towards the ME above the lower stratum of the trade in the middle layers, and the other towards the temperate and then polar zones around and above the MPHs, thus closing a circuit initiated at the pole (Figure 29).

8.6.1 Seasonal variation in general circulation

Variation in the Sun's radiation associated with its zenithal movement causes seasonal modifications in the intensity of meridional exchanges (Figure 29). All latitudes are affected to a greater or lesser extent, but it is the variations associated with the polar thermal deficit which have the most important effect on circulation, as they determine the dynamic of MPHs.

The winter thermal deficit increases the vigour of MPHs, intensifying confrontations in mid-latitudes, strengthening AAs, and accelerating the trades. Circulation is accelerated throughout the atmosphere in winter. The more meridional trajectory of MPHs displaces the most intense vertical transfers, and the corresponding westerly jet is in its turn shifted towards the tropics, now moving at maximum speed (twice that of the jet in summer).

The reinforced trade edges the ME in the direction of the summer hemisphere, and develops into the monsoon as it crosses the geographical equator. This crossing of the equator, requiring the support of the initial trade, is enhanced over tropical land masses in summer by deepening thermal lows which draw in monsoon air. The winter meteorological hemisphere therefore spills over to some extent into the summer hemisphere with its transequatorial monsoon fluxes (Figure 26).

Impelled by the trades, the monsoons are drawn into thermal lows; these are phenomena of the lower layers. Because of this, only the lower part of the ME is influenced by this 'overspill'. As a consequence, the ME possesses two vertical structures:

- In the middle layers, which are little (or not at all) influenced by lower layer phenomena, the vertical meteorological equator (VME) and, above it in the upper layers, the TEJ, take part in the overall shift of general circulation, similar to that of the AAs. The VME is the axis towards which easterly fluxes move in the middle layers (the upper strata of the trades).

- In the lower layers, the IME trespasses far into the opposite hemisphere, causing the trans-equatorial monsoon flux to move beneath the trade blowing in that hemisphere (Figure 30). The superposition of a trade upon a monsoon makes the IME a fundamental discontinuity, unproductive since the two fluxes have different origins, characteristics and directions.

Displacement continues as the seasons succeed each other: southward during northern winter, and northward during southern winter. In southern winter, the fact that the Earth is at aphelion reinforces the southern thermal deficit, which is already enhanced by the altitude of Antarctica (Figure 30). This situation encourages the spreading of the southern meteorological hemisphere, the incursion of well-supplied monsoons and the northward migration of the surface line of the ME, amplified by deep thermal lows over northern land masses (Figure 26).

8.6.2 Partitioning and stratification in circulation

As we saw in Chapter 7, modellers see the troposphere as uniform, homogeneous, and smooth, with neither partitioning nor discontinuity. Lindzen (pers. commun., 12 January 2004) wrote: '*there is a difference between sharp gradients and discontinuities, and it is the latter that do not exist*'. This 'ideal', but hypothetical, atmosphere has little in common with the real thing, which is, on the contrary, rigorously organised: it is separated into near-autonomous units of circulation and possesses vertical and horizontal discontinuities with distinct identities.

Circulation is first of all separated out in the lower layers (Figure 26). One of the primary discontinuities is relief, forming barriers at various altitudes and blocking the cold, dense air of MPHs. Consider, for example, both North and South America, where the west coasts have climatic characteristics distinctly different from those of eastern areas: MPHs of different origins come from different directions, as does precipitable water. The Great Escarpment around the southern African plateau prevents the maritime trade, blocked at the Namibian coast, from penetrating inland until it passes beyond the highlands of Angola, to flow into the lower lying Congo basin (Figure 27 above; Leroux, 1983).

The partitioned circulation thus created will possibly flow further into the tropical zone as a Trade Discontinuity (TD), a division between two trade wind circulations. Thus, in southern Mexico, the evolved Atlantic trade, rounding the Sierra Madre mountains, meets the nascent Pacific trade, which is denser, and rises above it (Figure 26). Similarly, south of the discontinuous barrier of the Cantabrian mountains, the Pyrenees, the Meseta, the Iberian Sierras, and the Atlas range in Morocco, a TD separates the Atlantic maritime trade from the continental Saharan trade which is energised by MPHs moving into northern Africa via the eastern Mediterranean basin. The warmer and lighter continental trade, with its load of dust, then passes above the cooler and denser maritime trade (Figure 26 above; Leroux, 1983).

Acknowledging the role of relief would preclude inanities like this one from Météo-France (Cours et Manuels No. 14, 2001, p. 152), on the subject of the Asian 'winter monsoon': '*the masses of cold air expelled from this thermal anticyclone experience considerable compression* (*a foehn effect*) *beneath the wind of the Himalayan and Tibetan relief*'. This seems to suggest that, contrary to all that is known about density, the very cold, dense, and thin layer air of the MPHs moving across China (Figure 26) manages to rise several thousand metres in order to cross the Himalayas and descend into the Indian subcontinent! This kind of 'explanation' is absurd, for reasons which ought to be borne in mind by those proposing so many similar dynamical 'links': the Pacific and the Great Plains of America?

In extra-tropical zones, the passage of MPHs sets up a synoptic and discontinuous stratification around and above the MPHs. The mobile inversion of wind, temperature, and humidity marking the top of the MPH separates fluxes of different origins, directions, vertical movement, and characteristics. Situated at an altitude of about 1,500 m in the vicinity of the pole, it progressively sinks as the MPH moves towards the tropics. The low-pressure corridors between MPHs possess no such inversion, and here, updrafts dominate in the cyclonic circulation.

The stratification becomes permanent and continuous within the AAs. An inversion at about 1,000 m separates air advected by MPHs from the subsident air above. This inversion, in concert with the anticyclonic character of the AA, is particularly unproductive (i.e., it inhibits the vertical development of cloud formations). It extends from the AA further into the trade circulation, becoming the equally unproductive TI. Beneath this horizontal discontinuity, the turbulent lower stratum warms up and may become moist (over the ocean) or drier (over land). Above, the subsident upper stratum is warm and dry. Between the two, the TIs mark the ceiling for thin stratiform clouds when the trade is a maritime one, or the upper limit of the concentrations of dust lifted by turbulence within the lower stratum of the continental trade.

The IME is another stratified, unproductive structure. The superposed fluxes (easterly trade above westerly monsoon) are of different origins, directions, and characters. Beneath such a structure, which may extend for several hundred (or even a thousand) kilometres (cf. Figure 26), precipitable water potential advected by the lower layer monsoon is scarcely exploited, with rain being normally absent (Leroux, 1983).

8.7 CONCLUSION: GENERAL CIRCULATION IS PERFECTLY ORGANISED

Whatever the modellers, with all their skills, might say, it is not the model which is right, but reality, the only possible reference. But **the models do not represent this reality**. **General circulation is complex, partitioned, stratified ... but perfectly organised**. When meteorological phenomena are labelled 'chaotic' (a comforting assertion for peace of mind), it is normally a sign of a (deliberate?) lack of understanding of this rigorous organisation. The fact is that 'chance' plays a small part, and introducing it is often the resort of unavowed ignorance.

So, when the supposedly 'unruly' climate is discussed, it is usually because those discussing it do not appreciate the '*rules*' (i.e., the rigorous mechanisms determining, localising, and characterising climates). Questions such as, '*Can the climate be turning on us*?' (Bard, 2004) are absurd, echoing the catastrophism of 'media weather', and serve only to point up an ignorance of the way in which climate works. 'Turning' suggests that the causes, mechanisms, or even the direction of general circulation really could, for some reason or other, abruptly change, or go 'turning' into reverse!

The general circulation of the atmosphere is rigorously organised, is always subject to the same physical principles, and always functions according to the same mechanisms (in well-defined geographical conditions). Its variations are therefore not variations in its nature, but are the result of variations in its intensity.

Before we claim that there is some relationship between two parameters, or, worse still, that one is the cause of the other, we must understand and recognise the respective places of each of these parameters, and the sequences linking them within the context of general circulation. We cannot say that something is tied to something else without having first established the reality of the physical link between them. No matter how sophisticated the statistical analysis, it is completely worthless climatologically if it is performed 'blind', with no basis in any proper meteorological analysis; observation and, above all, proof of the reality of physical links are indispensable.

Even if the schemas presented above, involving MPHs, are as yet incomplete, they represent the most realistic version (i.e., the version closest to meteorological reality), because they are based faithfully on direct observation. Let those who contest them, or query the role of MPHs at the origin of general circulation, supply proof that this concept does not conform to observed reality. Let them indeed suggest an alternative, indisputable concept, equally well supported, and based on the facts as they are observed!

The concept of the MPH as applied to general circulation has the advantage of representing, in the field of current research on this subject, the only schema embracing the initial cause of circulation, and the cause of its daily, seasonal, and indeed palaeoclimatic variations. It offers a complete and coherent overview of the dynamic of meteorological phenomena, encompassing all events, normal or extreme.

It is applicable to all scales of intensity, time, and space. This concept explains everything, leaving nothing out: **a concept that does not explain everything explains nothing**. This is why we shall constantly come back to it in the course of this book.