Oceanic Upwelling as a Key for Abrupt Climatic Change

By H. Flohn

REPRINTED FROM THE JOURNAL OF THE METEOROLOGICAL SOCIETY OF JAPAN
Vol. 60, No. 1, February 28, 1982

Oceanic Upwelling as a Key for Abrupt Climatic Change

By H. Flohn

Meteorological Institute, University of Bonn, Bonn
(Manuscript received 12 October 1981)

Abstract

Near the equator and along some coasts cool water ascends, together with the thermocline. This paper discusses on this phenomenon, which plays an important role in climatic change. The observed facts indicate as follows: a) A positive correlation between equatorial sea surface temperature and atmospheric content of CO_2 and H_2O, b) a negative correlation between the intensity of trades and equatorial (plus coastal) sea surface temperature, c) a negative correspondence between the intensity of the trades and the latitude of the subtropical anticyclone at the both hemispheres, d) a negative correlation between the tropospheric temperature difference, equator minus pole, and the latitude of the subtropical anticyclone, and e) a negative correlation between global temperature changes and the tropospheric temperature difference, equator minus pole, which is caused by the snow-ice-albedo-temperature feedback. A hypothetical hemispheric climatic feedback mechanism is, in the case of cooling after a cluster of volcanic eruptions: meridional temperature gradient will become greater, latitude of the subtropical anticyclones become lower, intensity of Hadley cell winds (trade) increases, equatorial sea surface temperature becomes cold, atmospheric content of CO_2 and H_2O becomes lower, thus resulting in further cooling. In the case of warming during a prolonged lull of volcanic activity, the tendencies mentioned above are opposite. This feedback mechanism changes drastically frequency and intensity of equatorial and coastal upwelling. Since the oceans are closed basin and the turnover time of the deep ocean may be in the order of 500 years, the efficiency of the process is limited in the time of several centuries.

1. Introduction

The concept of a geophysical climatic system embraces several interacting subsystems with quite different physical properties and characteristic time-scales (Fig. 1). Two of these subsystems are split into two layers also with different time-scales: the well-mixed troposphere versus the stable stratosphere, the upper mixed layer of the ocean (once described by A. Defant as "oceanic troposphere") versus the stable deep ocean. The transition zones between these two layers—the tropopause and the thermocline—are themselves complex, often multiple features continuously disintegrating and restoring, and thus quasi-permeable. In contrast to the atmosphere, the vertical exchange in the ocean is mainly concentrated in narrow areas, at the Antarctic ice shelves and in the northernmost Atlantic. Near the equator and along some coasts cool water ascends, together with the thermocline; here it is intended to show that this process plays a great role in climatic change. The role of the stratosphere in climatogenetic processes seems to be rather minor, while the deep sea acts as a major reservoir, especially in the carbon budget.

2. Cold water upwelling and atmospheric CO_2

The role of the carbon budget has arosed general interest among paleoclimatologists, after Delmas *et al.* (1980), Berner *et al.* (1980) and Oeschger (in Bach *et al.* 1980) found evidence in Antarctic and Greenland ice cores, that the CO_2-content of the atmosphere has varied between about 180 ppm during the last glacial (18 ka ago, ka $=10^3$ years) and about 350 ppm (perhaps 400 ppm) during the Holocene warm epoch 6-8 ka ago. Due to the recent wide-spread concern about the climatic consequences of the continuous increase of atmospheric CO_2 (Bach 1980), from about 295 ppm at the end of the 19th century to nearly 340 ppm (1981), the problem of the carbon budget in atmosphere,

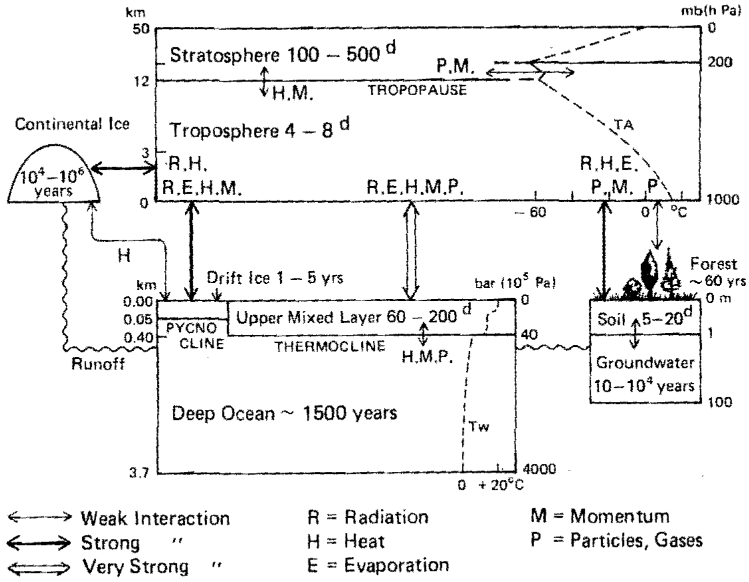

Fig. 1 Climatic system with its subsystems, interactions and characteristic time-scales (Flohn 1980).

ocean and biosphere is now thoroughly investigated. In this context it is impossible to review this issue; at present (August 1981) the most probable solution seems to be that the net carbon flux to or from the biosphere is nearly balanced, and that about 55 (45) percent of the fossil carbon enters the atmosphere (ocean). The recent increase of the CO_2-content of air varies distinctly from year to year, rather independent from the irregular annual increase of global CO_2-production from fossil fuel and cement, which has since 1973 decreased from about 4.5 percent to 2.25 percent per year (Rotty 1981). Comparative investigations (Keeling and Bacastow 1977, Newell *et al.* 1978, Angell 1981) found a positive correlation between the rate of increase of atmospheric CO_2 and the fluctuations of sea surface temperature (SST) in the equatorial Pacific, which are caused by rather abrupt changes between upwelling cool water and downwelling warm water ("El Niño") in the eastern equatorial Pacific. Indeed the cool upwelling water is not only rich in (anorganic) CO_2 but also in nutrients and organisms (algae) which consume much atmospheric CO_2 in organic form, thus reducing the increase of atmospheric CO_2. Conversely the warm water of tropical oceans, with SST near 27°C, is barren, thus leading to a reduction of CO_2-uptake by the ocean and greater increase of CO_2. The use of the local term "El Niño" from the Peruvian coast for this large-scale phenomenon—which occurs at about two thirds of the equatorial Pacific, and also seasonally at the Atlantic—cannot be recommended. A crude estimate of these differences is demonstrated by the fact that during the period 1958-1974, the average CO_2-increase within five selected years with prevailing cool water was only 0.57 ppm/a, while during five years with prevailing warm water it was 1.11 ppm/a. Thus in a warm water year, more than one Gt (10^{15} g) carbon is additionally injected into the atmosphere, in comparison to a cold water year.

3. Oceanic evaporation

Other investigations (*e.g.* Henning and Flohn 1980) have demonstrated that oceanic evaporation—as computed with the bulk aerodynamic formula—varies even stronger (and in the same direction) with upwelling/downwelling. During strong upwelling with SST <20 C, the evaporation drops to less than 1 mm/d, while at SST= 27-28C 4-4.5 mm/d are normal, equivalent to 140-160 cm/a. This difference is easily understood: with upwelling cold water the flux of sensible heat is directed downwards, thus stabilizing the air, trapping the evaporated water vapour in the lowest layers and reducing the evaporative power of the air with increasing relative humidity. Above warm waters, the air is heated from below and thus unstable, water vapour is transported rapidly upward with atmospheric turbulence and the relative humidity cannot increase above a certain threshold (near 78 percent). In this case evaporation reaches its maximum, thus consuming (with a Bowen ratio between 0.03 and 0.05) nearly the whole available net radiation. On the base of 120 monthly averages at the equatorial Atlantic Weber (1981) has found a significant positive correlation (+.78) between SST and latent heat of evaporation. Similarly a significant negative correlation (−.83) exists between relative humidity and thermal stability, *i.e.* the difference SST-T_{air}. A positive correlation between rainfall (as indicating convective activity and thermal instability) and SST has been found by many authors; it has also been found in a fairly realistic model by Rowntree (1972).

In passing it should be noted that with a net radiation prescribed by the geometry of solar radiation and high convective cloudiness, this process limits SST at undisturbed ocean areas. This is caused by the exponential increase of saturation vapour pressure with SST: above about 29 C (at a maximum 29.5 C) the available net radiation—see Hastenrath and Lamb (1978, 1980)—is no longer sufficient to maintain the process of evaporation. Indeed, only in parts of the Indian Ocean, in the Indonesian seas and in the westernmost Pacific SST values slightly above 29 C are observed. Assuming the solar radiation to be virtually constant, this gives apparently an upper limit of SST.

4. Physical processes

What physical mechanism is responsible for the sudden and nearly simultaneous shifts between upwelling and downwelling in the central and eastern part of the Pacific Ocean? Wyrtki (1975, 1977) has collected convincing evidence that in a closed basin, the zonal circulation of water masses driven by easterly winds at both sides of the equator, reverts its sign, when the wind stress of the easterlies drops, in the Central Pacific, below a certain threshold. Then the piled-up water in the western part flows back driven by a surface slope in order of 0.5 m ($\sim 5\cdot 10^{-8}$) along the length of the Pacific equator. At the equator strong easterly winds create a narrow belt of Ekman divergence in the upper mixed ocean layer and consequently of upwelling (J. Bjerknes 1969); the vertical component of oceanic motion is controlled by the vorticity of the wind stress vector. The lull of the easterlies then causes a disappearance of upwelling and the replacement of cool water by normal tropical water. E. R. Reiter (1978) has also shown that equatorial upwelling is correlated with more intense, downwelling with comparatively weak trade winds. It should be noted that these processes occur nearly simultaneously also over the adjacent areas of coastal upwelling (Enfield and Allen 1980) and (somewhat weaker) at the eastern Pacific belt Lat. 20°N-20°S (Weare 1981).

Under stationary conditions—*i.e.* disregarding the present continuous injection of CO_2 into the atmosphere—the air-sea exchange processes of CO_2 and H_2O act parallel: upwelling reduces, downwelling increases their content in the air. This coherence adds to the corresponding role of CO_2 and H_2O in comprehensive climate models (*e.g.* Manabe-Wetherald 1975, 1980, Ramanathan 1981). These two gases are most powerful absorbers of infrared radiation in the atmosphere, but are transparent in the visible part of the spectrum. Both contribute to the so-called "greenhouse effect"; that of H_2O is even greater, especially in the tropics, than that of CO_2, since the global averaged partial pressure of H_2O at the surface is 2.5 mbar (Trenberth 1981) compared with that of $CO_2 \sim 0.3$ mbar. A hierarchy of models has indicated that with a doubling of the CO_2-content the global averaged surface temperature (T_{sf}) is expected to rise between 2 and 3 C (Gates in Bach 1980). Due to the well-known snow-ice-albedo-temperature feedback (Kellogg 1974) the temperature rise at the northern polar cap is 2-3 times larger than in mid-latitudes; in the tropics it seems to be slightly smaller. This indicates that the tropospheric temperature difference Γ between equator and pole decreases with increasing CO_2 and vice-versa (Fig. 2). A reasonable estimate of the change $\Delta\Gamma$ with T_{sf} can be expressed linearly

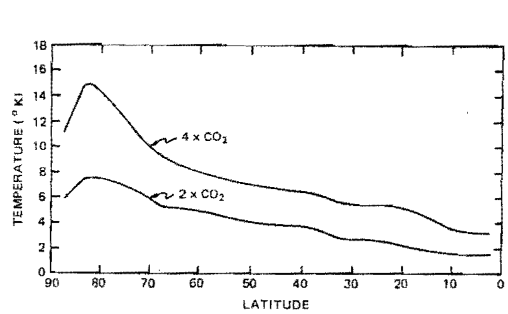

Fig. 2 Surface temperature as a function of latitude after an increase of atmospheric CO_2 content by a factor 2 or 4 (Model Manabe-Wetherald 1980; L. Gates in Bach 1980).

$\Delta\Gamma = -K\Delta T_{sf}$ (Flohn 1981)
with an amplification factor K to be derived *e.g.* from the model results of Manabe-Wetherald (1975, 1980). For the layer 300/700 mb average monthly values of Γ are available for both hemispheres (Flohn 1967); K can be estimated to be ~1.4. If, with a prolonged intense warming in the order of $\Delta T_{sf}=4\text{-}5°$, a possible disappearance of the Arctic sea-ice is taken into account (Flohn 1980), together with a vanishing surface inversion, K may rise to 1.5-1.7 (Flohn 1981). However, in the case of a water-covered, unglaciated planet, K should drop below 1. Under actual conditions a strong positive correlation (+0.85, with a 1-2 month lag of φ_{STA} 0.92) exists between Γ and the latitude of the subtropical anticyclone (φ_{STA}) at both hemispheres (Korff and Flohn 1969). This relation had originally been derived (Flohn 1964) from a baroclinic instability criterion given by Smagorinsky (1963), but is empirically verified (Fig. 3).

These observed facts indicate that significant interacting correlations and correspondences between atmospheric and oceanic phenomena exist:

a) a positive correlation between equatorial SST and atmospheric content of CO_2 and H_2O,
b) a negative correlation between the intensity of trades and equatorial (+coastal) SST,
c) an (apparent but not checked) negative correspondence between the intensity of the trades and φ_{STA},
d) a negative correlation between Γ and φ_{STA},
e) a negative correlation between global temperature changes and Γ, caused by the snow-ice-albedo-temperature feedback.

For a first-order estimate subject to further verification we disregard in these correlations some short time-lags, in the order of a few months, as investigated by Wyrtki (1975), Reiter (1979), Angell (1981) and others.

5. Feedback mechanism

Combining these correlations and correspondences at a hemispheric scale, an integrated feedback mechanism should act as follows (Table 1):

A similar mechanism may also be responsible for the hitherto rather enigmatic occurrence of abrupt climatic change (*e.g.* Kukla 1980, Woillard 1979, Flohn 1979). During the last years convincing evidence for non-local drops of annual temperature in the order of 3 C and more in less than a century, perhaps in a few decades, has

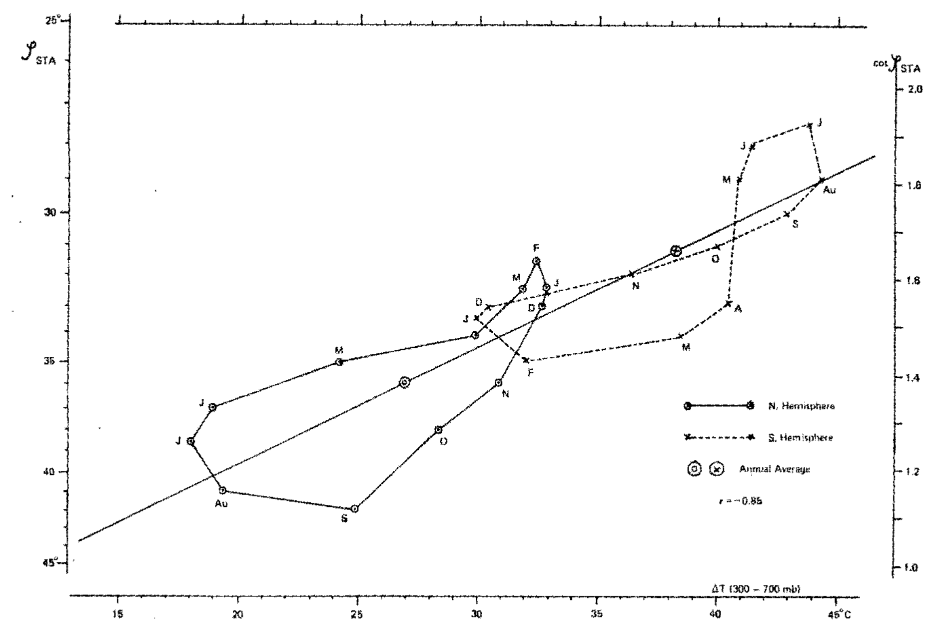

Fig. 3 Average monthly and annual values of the tropospheric (300-700 mb layer) temperature difference equator-pole versus latitude of the subtropical anticyclonic belt, both hemispheres, actual data (revised after Korff-Flohn 1969).

Table 1 A hypothetical hemispheric climatic feedback mechanism

Polar regions initially	cooling[1]	warming[2]
Meridional temperature gradient	↗	↘
Latitude of subtropical anticyclones φ_{STA}	↘	↗
Intensity of Hadley cell winds (trades)	strong	weak
Equatorial sea surface temperature (SST)	cold	warm
Atmospheric content of CO_2 and H_2O	↘	↗
Resulting in further	cooling	warming

[1] e.g. after a cluster of volcanic eruptions
[2] e.g. during a prolonged lull of volcanic activity

been presented. The last examples of this kind had been observed in the late-glacial "Alleröd-sequence", when in Europe two sudden warmings (Bölling and Alleröd) occurred alternatively with two abrupt coolings (Middle and Lower Dryas period) during not more than 1,500 years, between 12.3 and 10.8 ka ago. Simultaneous events have been evidence also in North America, accompanied by at least a couple of drastic changes of temperature and rainfall in the tropics of South America, Africa and in NW India. Similarly dramatic climatic "catastrophes" have been described from earlier interglacials (Müller 1978). They are very rare events, with a frequency in the order of one in $1\text{-}2\times10^4$ years.

6. Discussion

As suggested above, the hemispheric climatic feedback mechanism changes drastically frequency and intensity of equatorial and coastal upwelling. Since the oceans are, to some extent, closed basins, and since the turnover time of the deep ocean may be in the order of 500 years only (Broecker *et al.* 1980), the efficiency of the processes is limited in time; after several centuries it should drop asymptotically. But just this time-scale of a few decades or centuries is of interest for paleoclimatologists.

While the correlations a)-e) (and their consequences) apparently are rather well established, the relevant time-lags are less certain and should be verified, with sufficiently long and reliable data series, in the space-time domain. This check promises also to give a hint of the sign of the causal geophysical relationships. At present, the sign of the vertical component of the oceanic motion along the Pacific equator varies at a time-scale of a few years or even shorter. It is not known, how the frequency of such shifts, or the duration and intensity of upwelling changes with time, *e.g.* between the last decades of the 19th century and the period since 1950 (which is unfortunately the only period with a fairly satisfactory density of observations). It is even less known how far duration and intensity of upwelling/downwelling episodes changed in prehistoric periods, such as during the Holocene warm period 6-9,000 years or during the last glaciation. Strong carbonate sedimentation at the Ontong-Java plateau around 155°E (Berger 1977) and phosphate sediments at Nauru indicate, that during the glacial peaks upwelling was much more intense and/or frequent in the western Pacific than now; SST along the equator was 6-8° lower.

The behaviour of the equatorial interaction between atmosphere and ocean, involving exchange of H_2O and CO_2 between both reservoirs, is only incompletely understood under present conditions. Our hypothesis of larger variations of this mechanism during climatic changes promises a deeper insight into their geophysical, *i.e.* internal causes, most probably related to a time-scale of a few decades or centuries, *i.e.* to the "human" time-scale in the order of the human life-time (50-100 years). Since this time-scale remained until now quite enigmatic, but is of high concern for mankind in a time of rapid population increase and depletion of resources, further investigations must be strongly recommended.

References

Angell, J. K., 1981: *Monthly Weather Review,* **109**, 230-243.

Bach, W., J. Pankrath and J. Williams, eds. 1980: *Interaction of Energy and Climate.* D. Reidel Publ. Comp., XL+569 pp.

Berger, W., 1977: In: N. R. Andersen, A. Malahoff, eds.: *Marine Science,* **6**, 505-542.

Berner, W., H. Oeschger and B. Stauffer, 1980: *Radiocarbon*, **22**, 227-235.

Bjerknes, J., 1969: *Monthly Weather Review*, **97**, 163-173.

Broecker, W. S., T. H. Peng and R. Engh, 1980: *Radiocarbon*, **22**, 565-598.

Delmas, R. J., J. M. Ascencio and M. Legrand, 1980: *Nature*, **284**, 155-157.

Enfield, D. B. and J. S. Allen, 1980: *Journ. Phys. Oceanogr.*, **10**, 557-578.

Flohn, H., 1964: *Geol. Rundschau*, **54**, 504-515.

————, 1967: *Ann. Meteor., N.F.*, **3**, 76-80.

————, 1979: *Quaternary Research*, **12**, 135-149.

————, 1980: *Possible Climatic Consequences of a Man-Made Global Warming*. Int. Inst. Appl. Syst. Anal. Laxenburg, RR-80-30, XII+80 pp.

————, 1981: *Physikalische Blätter*, **37**, 184-190.

Hastenrath, St. and P. Lamb, 1978: *Heat Budget Atlas of the Tropical Atlantic and Eastern Pacific Ocean*. Univ. of Wisconsin Press.

———— and ————, 1979: *Climatic Atlas of the Indian Ocean Part II*. Univ. of Wisconsin Press.

Henning, D. and H. Flohn, 1980: *Contrib. Atmos. Phys.*, **53**, 430-441.

Keeling, J. D. and R. B. Bacastow, 1977: In: *Energy and Climate*. Nat. Acad. Sci. Washington, pp. 72-95.

Kellogg, W. W., 1973: In: G. Weller, S. A. Bowling eds.: *Climate of the Arctic*, Fairbanks, 111-116.

Korff, H. Cl. and H. Flohn, 1969: *Ann. Meteor., N.F.*, **4**, 163-164.

Kukla, G., 1980: *Palaeoecology of Africa*, **12**, 395-408.

Manabe, S. and R. T. Wetherald, 1975, 1980: *Journ. Atmos. Sci.*, **32**, 3-15; **37**, 99-118.

Müller, H., 1979: In: W. Bach *et al.* ed.: *Developm. Atmos. Sci.*, **10**, 29-41.

Newell, R. E., A. R. Navato and J. Hsiung, 1978: *Pure and Applied Geophysics*, **116**, 351-371.

Ramanathan, Y., 1981: *Journ. Atmos. Sci.*, **38**, 918-930.

Reiter, E. R., 1978: *Monthly Weather Review*, **106**, 324-330.

————, 1979: *Colorado State Univ., Environm. Res. Paper*, **21**, 62 pp.

Rotty, R., 1981: Lecture given at a CO_2-Symposium, Bern (September 1981).

Rowntree, P. R., 1972: *Quart. Journ. Roy. Meteor. Soc.*, **98**, 290-321.

Trenberth, K., 1981: *Journ. Geophys. Res.*, **86**, 5238-5246.

Weber, H., 1981: Unpublished paper, Univ. Bonn.

Woillard, G. M., 1979: *Nature*, **281**, 558-562.

Wyrtki, K., 1975, 1977: *Journ. Phys. Oceanogr.*, **5**, 572-584; **7**, 779-787.

突然の気候変化の鍵としての海洋の湧昇

H. Flohn

Meteorological Institute, University of Bonn

赤道付近および2～3の海岸に沿って，水温躍層とともに冷水が上昇する。この論文は気候変化に重要な役割を果すこの現象について論じた。観測した事実は次の通りである。a）赤道の表面海水温と大気中の CO_2 や H_2O の量は正相関がある。b）貿易風の強さと，赤道（＋沿岸）表面海水温は負の相関がある。c）貿易風の強さと両半球の中緯度（亜熱帯）高気圧との間には負の対応がある。d）赤道と極の間の対流圏の気温差と中緯度の亜熱帯高気圧とは負の相関がある。e）地球の気温変化と雪-氷-アルベドー-気温のフィードバックによってもたらされる赤道と極の間の気温差とは負の相関がある。火山爆発が盛んであった時期後の寒冷化の場合の半球規模の気候のフィードバックの機構は次のように考えられる。すなわち，連続的火山爆発後の寒冷な時代には子午線方向の気温傾度は大となり，亜熱帯高気圧の軸は低緯度側に移り，ハードレイセルの風（貿易風）の強さは大となり，赤道の表面海水温は低下し，大気中の CO_2 と H_2O は減少し，さらに気候は寒冷化する。火山爆発が休止状態の温暖な時代には，上記の傾向は逆となる。このようなフィードバックの機構は赤道や沿岸湧昇の頻度や強さを根本的に変える。しかし，海洋は閉じた系であり，また深海の入れ代りの時間スケールは500年のオーダーであるから，上述の過程の効果は数世紀の時間に限られるであろう。

The Periodicity and Predictability of Climate: An Essay

By Zhang Jia-cheng

Central Meteorological Bureau of China, Beijing
(Manuscript received 16 September 1981)

Abstract

The atmospheric processes are usually presented through the phase of spatial waves and/or of temporal periods as units. Owing to the limited size of the Earth, temporal periods has more generality in identification of atmospheric processes with different dimensions. There are several categories of atmospheric periodicities different not only in dimension, but also in nature and causes of formation. That is the storeyed structure of atmospheric processes. For singling out the basical aspects of climatic processes in a given dimension, scale correspondence is an important working principle. Among the processes in different storeys there also exist close relationships. Generally speaking, the macro-phase is the background of micro-processes. A certain mutation of individual micro-process in its turn may imply some information about the transition of macro-phases. So the structural analysis of atmospheric processes gives the idea of their predictability in any time scale. That is the conditional quasi-predictability which would be beneficial to make the methodology of climate prediction more rationalized.

Periodicity is a question of fundamental importance in climate and its predictions. But, no prominent period had ever been found in atmosphere and recognized unanimously by scientific circle, besides the diurnal and annual variations. This does not mean nonexistence of periodicity in the atmosphere. As well as in other natural and social phenomena, the periodicity does exist in general. Owing to the great complexity in scale and in nature, atmospheric periodicity is a kind of conditional quasi-periodicity. Without considering the conditions and approximation, nothing effective could be done in period studies, as it had been shown by the previous works in this field. The concept of conditional quasi-periodicity widens the perspective of climatic prediction research. In connection with this, the predictability of climate would be conditional quasi-predictability in character. Some discussions in these aspects are given as follows.

1. The spectrum of atmospheric processes

The atmospheric processes are usually presented through the phases of spatial waves (for example: high and low pressure systems, troughs and ridges, etc.) or of temporal periods (for example: rain processes, natural synoptic periods, natural synoptic seasons, wet and dry stages of many years, etc.) as units, just like molecules cellules are the units of a living organism. When a wave passes over a station, there naturally will be a fluctuation on the temporal curves of relevent meteorological elements observed there. Between the spatial waves and temporal periods the relationship is nearly lineal in the extent of synoptic scale. Although weather forecasting takes the spatial phases as its main object of analysis, but naturally the temporal periods considered implicitly. For example, a cooling or a rain process not only is the result of pressure wave activities on synoptical maps, but also are very prominant on temporal curves of temperature, rainfall, etc. On time coordinate weather prediction and climate prediction are similar. But the climate prediction takes the temporal phases (or stages), not the spatial phases, as its main object. To make this idea more clear, the discussion starts from Fig. 1, on which the spectrum of atmospheric processes is shown. The coordinate is given in years and kilometers (both in logarithm).

The synoptical scale is defined by the resolution limitation of the instantaneous synoptic charts. The smallest in extent synoptic chart is