The general circulation of the atmosphere

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1 INTRODUCTION

The main goal of this module of the ECMWF training course is to give some information about the ability of General Circulation Models (GCMs) in general (and of the ECMWF global models in particular) to represent the main characteristics of the Atmospheric General Circulation (AGC). It is well known that GCMs show systematic deficiencies in representing the earth's atmospheric climate. Such deficiencies are often referred to as Systematic Errors (SEs) or as the models' Climate Drift. This last term expresses clearly the main essence of the problem: when a GCM integration is initiated from real-data initial conditions (that is from a single realisation of the observed distribution of atmospheric states, the 'climate'), a progressive drift takes place from that single realisation of the real climate towards the model's own climatic distribution. Not only climate modellers suffer from this, but also numerical forecasters. We will see how the climate drift (or the progressive onset of the systematic error) is also an important source of forecast error.

In order to be able to diagnose and describe model deficiencies in representing the observed circulation, we need first to describe the real atmosphere, albeit in a synthetic way. The purpose of these first two lectures will indeed be: describing the observed mid-latitude AGC and the main physical processes responsible for it. We will then try to describe model deficiencies in representing it and this will put us in a position to make hypotheses on the possible causes for SEs, depending upon their structure, characteristics and evolution properties.

2 THE INTEGRAL ENERGY BALANCE AND THE EXTERNAL THERMAL FORCING

We shall start from describing the overall (integral) observational framework at the basis: the integral energy balance.

Many physical processes are involved in energy exchanges between the various components of the climate system. Fig. 1 gives some quantitative (annually averaged) estimates of the energy exchanges between these components, referred to in 100 units of incoming solar radiation (actually equal to 344 W m^{-2} if averaged over a long time and over the entire earth's surface, which is one quarter of the solar constant). We can see from Fig. 2 that 30% of this energy is immediately reflected back into space in the form of short waves. This is mostly due to the high reflectivity of clouds, although the air itself backscatters approximately 6% and the earth's surface (mainly the deserts and the oceans) reflects another 4%. The remaining 70% is absorbed by atmospheric components (water vapour, ozone, dust etc. : 16%), clouds (suspended liquid water: 3%) and by the surface of the earth (both oceans and land: 51%, by far the greatest amount). It is then mostly the surface which has to communicate this energy to the atmosphere, via sensible (7%) and latent (23%) heat fluxes and via long wave radiation, absorbed by water vapour and carbon dioxide (15%). The net energy input into the atmosphere is then (16+3+7+23+15) = 64% of the total solar input. This energy, if there has to be no long term heating or cooling of the atmosphere, has to be ultimately radiated back into space, and this is done mostly by water vapour and carbon dioxide (38%) and clouds (26%).

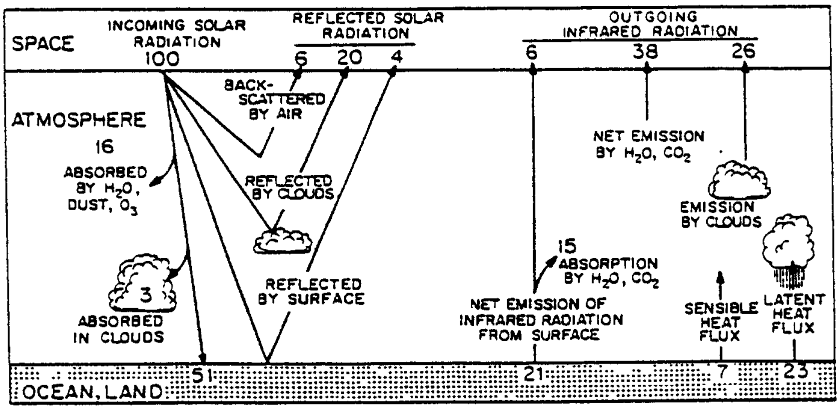


Figure 1. The annual mean global energy balance for the earth–atmosphere system. Numbers are given as percentages of the globally averaged solar irradiance incident upon the top of the atmosphere.

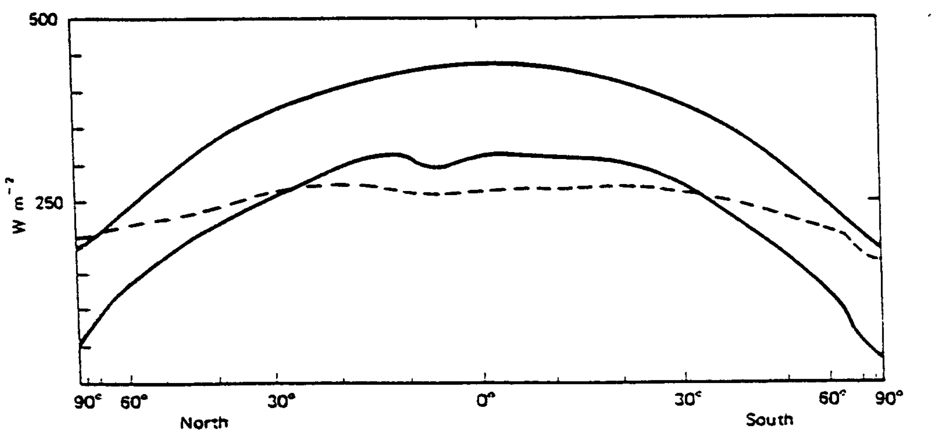


Figure 2. The radiation balance of the earth. The upper solid curve shows the average flux of solar energy reaching the outer atmosphere. The lower solid curve shows the average amount of solar energy absorbed. The dashed line shows the average amount of outgoing radiation. The lower curves are average values from satellite measurements between June 1974 and February 1978, and are taken from Volume 2 of Winston *et al.* (1979). Values are in W m^{-2}. The horizontal scale is such that the spacing between latitudes is proportional to the area of the earth's surface between them, i.e. is linear in the sine of the latitude.

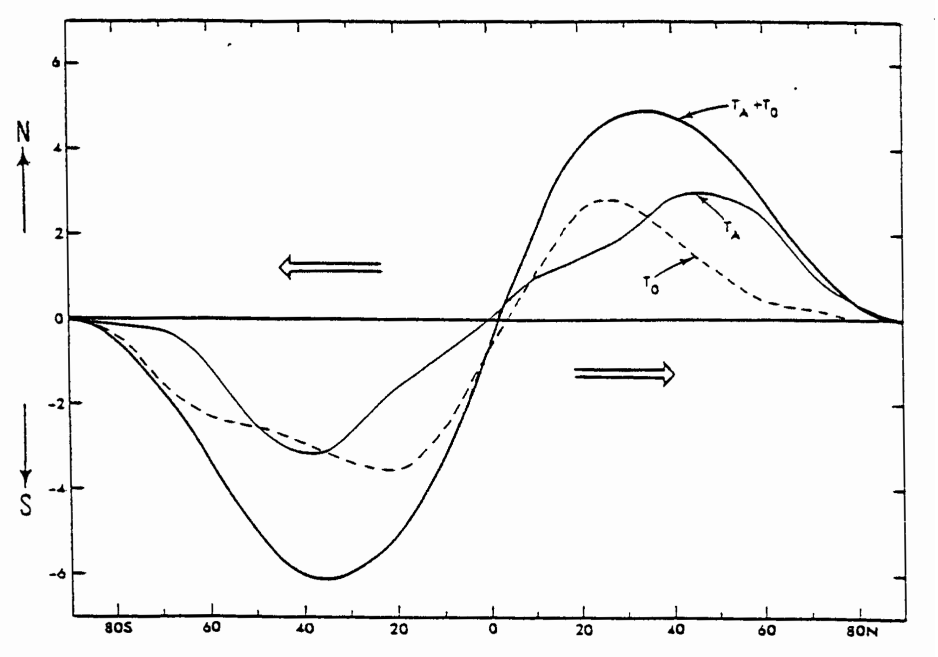


Figure 3. Zonal mean profiles of the northward transports of energy in the atmosphere–ocean system (T_A+ T_0) based on radiation requirements, in the atmosphere (T_A) obtained from rawinsonde data, and in the ocean (T_0) inferred as a residual. All curves are for annual mean conditions in 10^{15} W. Positive values indicate northward transports.

The solar heating input, however, is strongly latitudinally inhomogeneous, being much larger in tropical than in polar regions (see Fig. 2). This would create very large low-level latitudinal temperature gradients (because most of the heat input comes from the lower boundary). These would immediately reflect in density (and therefore pressure) gradients which are incompatible with an atmospheric state of rest (or, better, of solid body rotation). Atmospheric large scale motions are therefore the consequence of such gradients (see Fig. 3). The air motions, however, take place in a rotating frame of reference and their dynamics must be understood taking the earth's rotation into account.

A simple and very useful conceptual laboratory model to illustrate these processes is the rotating annulus.

3A CONCEPTUAL MODEL: THE ANNULUS EXPERIMENT

Annulus experiments can provide a (partial) conceptual model of the General Circulation which can be very useful in understanding some of the basic and fundamental processes which are at the basis, e.g. the behaviour of the atmosphere as a heat engine transporting heat from the poles to the equator in a rotating frame of reference.

The experimental apparatus is composed of two coaxial cylinders resting on a base and rotating around their common axis. The gap between the two cylinders is filled with fluid which, if the system is isothermal, rotates at the same angular speed as its container. If, however, the outer cylinder is heated and the inner one is cooled (and they, in turn, heat and cool the adjacent fluid) density gradients are created in the rotating fluid requiring motion to balance them. Such motions will, initially, be in the radial direction (‘north–south’). But as soon as fluid parcels start moving in a rotating frame of reference, the Coriolis force takes action, deflecting their motion at right angles to the velocity vector (and to the right, for anticlockwise rotation), until an approximately geostrophic balance is attained, with low-level easterlies (and a weaker southward meridional flow) and upper-level westerlies (and a corresponding northward meridional flow). This Hadley-type circulation is very similar to the observed Hadley cell in the earth's NH tropical regions.

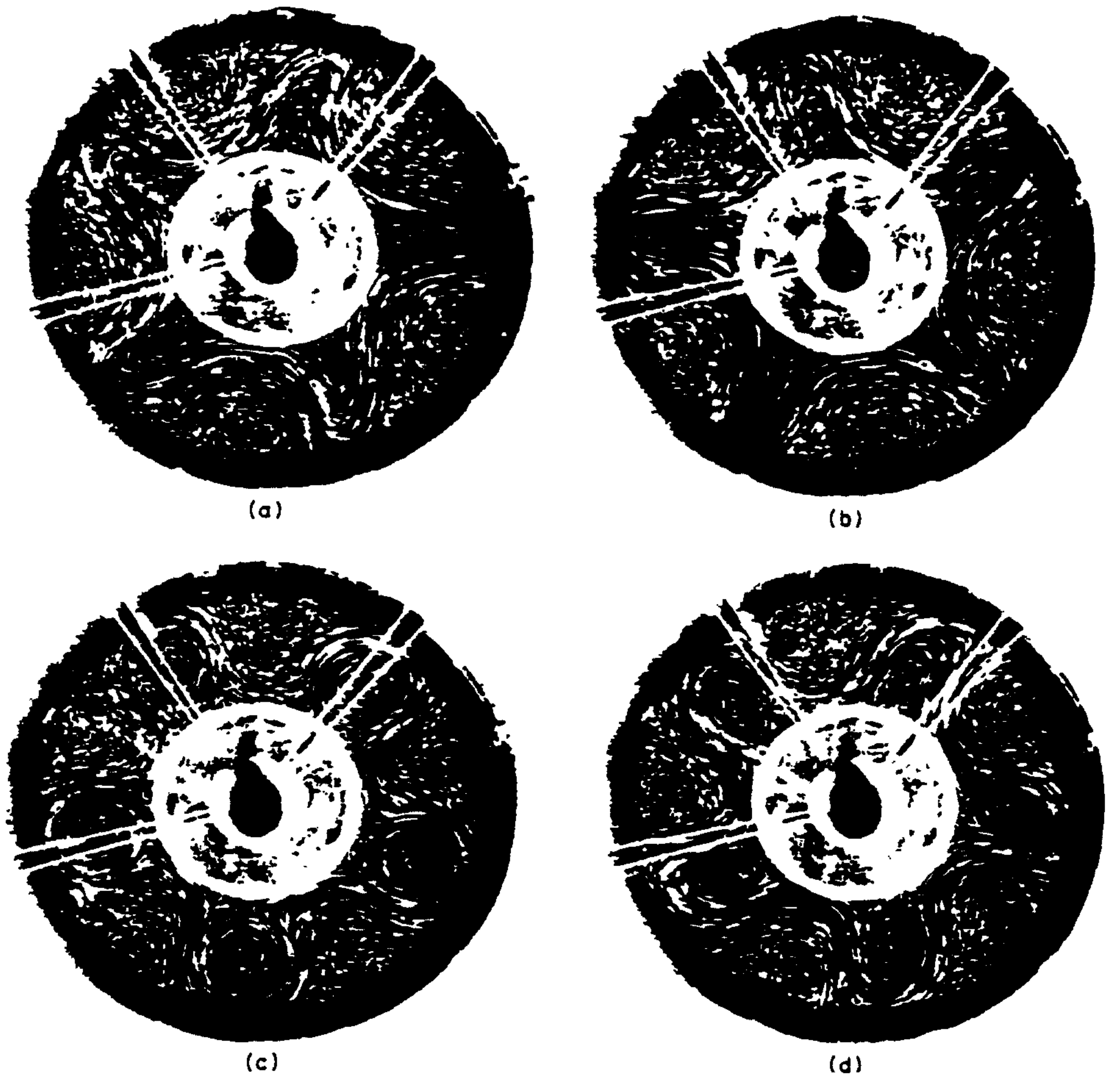


Figure 4. Time exposures showing the motion of surface tracer particles in a rotating annulus. The four photographs illustrate various stages of a five-wave tilted trough vacillation cycle. The period of the vacillation cycle is $16\frac{1}{4}$ revolutions and the photographs are at intervals of 4 revolutions. (Photographs by Dave Fultz).

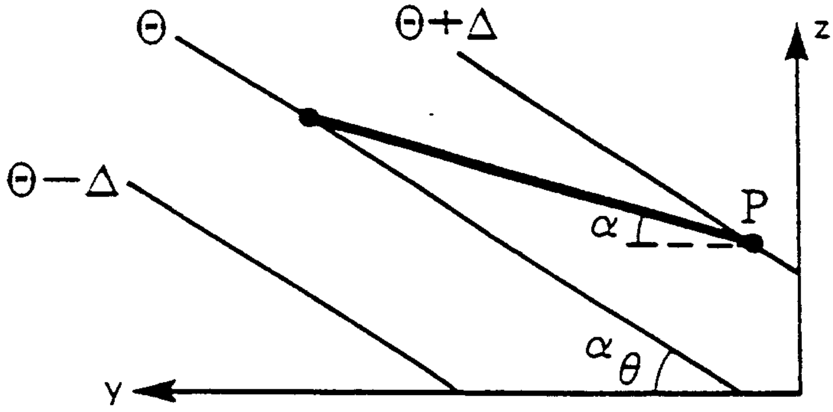


Figure 5. Basic isentropes at an angle α_θ and a displacement at an angle α.

If the latitudinal thermal gradients are progressively increased, this simple and symmetric zonal regime becomes baroclinically unstable, and waves of progressively smaller and smaller wavelength start appearing (see Fig. 4). These waves grow at the expense of the available potential energy of the zonal mean flow and are possible because potentially warmer (and, therefore, lighter) parcels of fluid are transported upward and poleward and potentially colder (and, therefore, heavier) parcels are transported equatorward and downward, thereby lowering the centre of gravity of the entire system (see Fig. 5). Their main purpose is to increase the efficiency of the N–S transport of beat, to make it compatible with the increased temperature gradient, since the symmetric Hadley circulation is inefficient in transporting heat N–S.

The large-scale waves so produced in the annulus resemble closely the large-scale waves that dominate the mid-latitude tropospheric circulation of the real atmosphere, but this resemblance can be partially misleading. We will, in fact, see in a later lecture how the planetary-scale atmospheric waves could well exist in a purely barotropic atmosphere, solely due to the latitudinal variation of the Coriolis parameter, while we have just seen that in the annulus such waves are purely baroclinic. In reality, planetary waves are ruled by a mixed barotropic–baroclinic dynamics, in which both conversion between available potential energy and kinetic energy of the zonal flow and kinetic energy of the waves are important.

4THE ENERGY AND MOMENTUM BUDGETS: THE ROLE OF THE EDDIES

We will now discuss the energy cycle of the AGC by means of the so-called Lorenz box diagram. Fig. 6 shows an example of the diagram. The four main boxes represent available potential energy (PE) and kinetic energy (KE), while upper boxes contain energy terms of the zonal mean flow and lower boxes energy terms due to the eddy departures from the zonal mean. Arrows between boxes represent conversion terms, and therefore processes responsible for them. Conversions between PE and KE are due to baroclinic processes, while conversions between zonal and eddy KE are due to barotropic processes. For exact derivations of the energy and conversion terms in a quasi-geostrophic approximation, the student is referred to Holton's (1979) textbook.

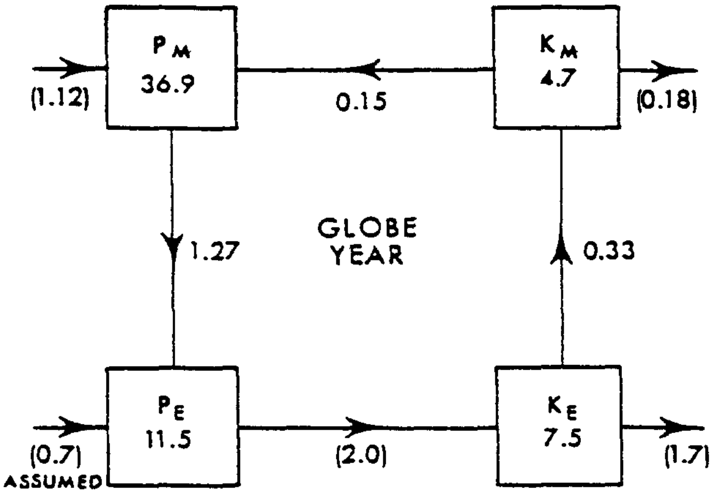


Figure 6. The observed energy cycle for the global atmosphere. Energy amounts inside each box are given in 10^5 J m^{-2}, and rates of generation, conversion and dissipation in W m^{-2}. Terms not directly measured are shown in parentheses.

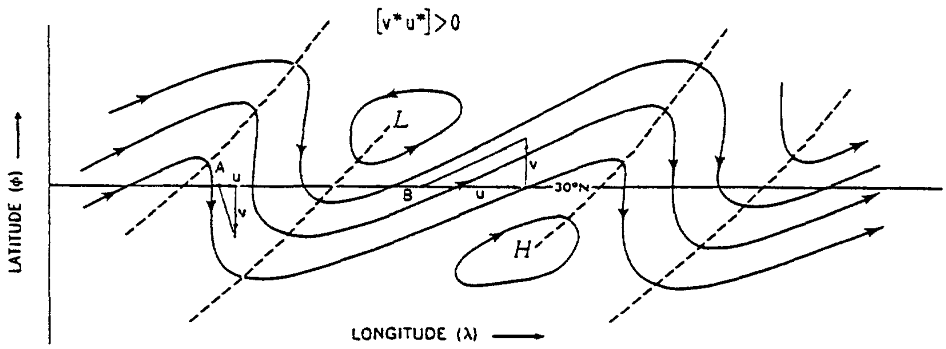


Figure 7Schematic picture of the dominant mechanism of northward transport of momentum by eddies in mid-latitudes of the northern hemisphere.

The solar heating provides input in the PM and PE boxes (to understand why in the PE box as well, think of the longitudinally inhomogeneous cloud cover), while dissipative processes provide output from KM and KE boxes (dissipative processes require motion, and therefore kinetic energy to take place). The mean meridional circulations are responsible for CZ conversions (but they are small); such symmetric zonal circulations are, however, baroclinically unstable. This instability, together with the presence of large-scale mountains and land–sea contrasts, generate eddies that are responsible for both CA (available zonal to available eddy) and CE (available eddy to kinetic eddy) energy conversions, and therefore to the main baroclinic energy cycle, whose main task is to transport heat in the north–south direction in a more efficient way than a symmetric Hadley-type circulation could do. Such eddies, however, due to the N–S tilt of their axes, also transport momentum in the N–S direction (see Fig. 7). This property is essential because it is the convergence of the latitudinal flux of momentum due to the eddies (together with the convergence of vertical eddy momentum flux), see Fig. 8 , that maintains those large-scale, meandering ‘tubes’of concentrated westerly momentum characteristic of the mid-latitudinal atmosphere, called jet streams. The position and intensity of such jets is therefore determined by subtle energy and momentum balance requirements.

This can also be inferred by looking at the precise geographical relationships between the meanders of the mean 500 hPa NH flow (see Fig. 9 (a)) and the time variance due to all transient eddies of short periods (Fig. 9 (b)) and to eddies of longer periods (Fig. 9 (c)). It is evident how high-frequency eddies tend to be generated more in the jet exit regions, while low-frequency eddies have their highest activity in correspondence of the highest flow diffluence.

We can conclude this section by underlining how important the interactions between the eddies and mean flow are. The eddies exist because the mean flow is both unstable and subjected to non-axisymmetric boundary conditions, but the essential mean flow characteristics are, in turn, heavily dependent upon the eddies themselves. Any GCM that aims at representing satisfactorily the mean state of the atmosphere and its variability around this mean state should therefore correctly model these eddy/mean-flow interaction.

5 THE EXISTENCE OF CIRCULATION REGIMES

Already very simple annulus experiments show that ultimately turbulent systems with very many degrees of freedom can exhibit different ‘regimes’ of motion that can coexist in the presence of the same external forcing parameters. During the last few years, convincing evidence has been found that some atmospheric observables, notably connected with planetary-scale wave activity during winter, have non Gaussian distributions, see Fig. 10 . The earth's atmosphere can (and does) therefore span the phase space of its possible realisations in a non-simple way.

The existence of such weather regimes has important implications on several aspects of atmospheric science, from climatology (and the very definitions of climate and of general circulation) to weather forecasting and general circulation modelling. We will see in a later lecture how the occurrence of a well known synoptically defined weather regime, that is blocking, affects the skill of the ECMWF operational model.

6 SUMMARY AND CONCLUSIONS

The latitudinally dependent solar input establishes thermal gradients between poles and equator. Such gradients will result in pressure gradients and therefore in atmospheric motions. The atmosphere is rapidly rotating so that geostrophic balance will approximately establish. Together with hydrostatic balance, they will initially set up a Hadley-type symmetric circulation in thermal wind balance. This circulation, however, will never be observed in reality because it is baroclinically unstable and because mountains and land–sea contrasts will generate eddies. Such eddies make the pole-to-equator heat transport more efficient and decrease the thermal gradients. Eddies, however, transport momentum as well, both vertically and latitudinally. The spatial structure of the eddy/mean-flow interactions is such that regions of enhanced (or decreased) zonal flow are created due to either north–south or vertical convergence (or divergence) of eddy momentum flux. Such regions are the so-called jet streams. The subtle relationships between the eddies and the mean flow govern, therefore, the observed climate and are a crucial benchmark test for diagnosing systematic model deficiencies.

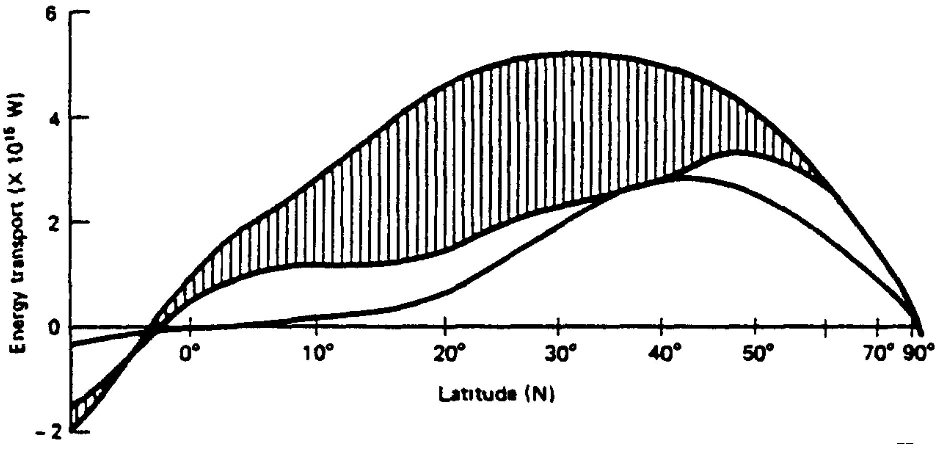


Figure 8. The northward transport of energy (in units of petawatt = 10^{15} W) as a function of latitude. The outer curve is the net transport deduced from radiation measurements. The white area is the part transported by the atmosphere and the shaded area the part transported by the ocean. The lower curve denotes the part of the atmospheric transport due to transient eddies and is the mean of the monthly values from Oort (1971, Table 3). The horizontal scale is such that the spacing between latitudes is proportional to the area of the earth's surface between them, i.e. is linear in the sine of the latitude.

(a)

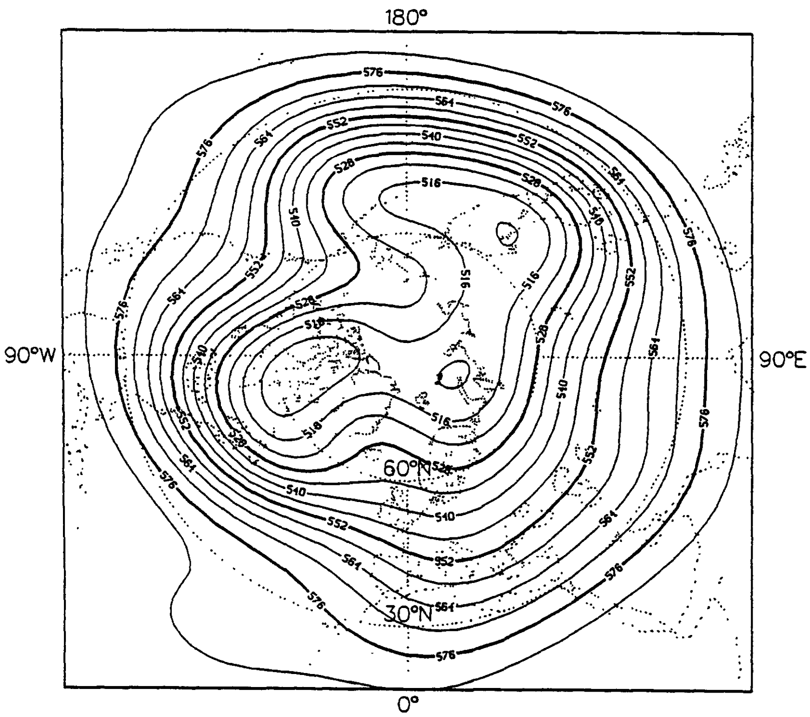
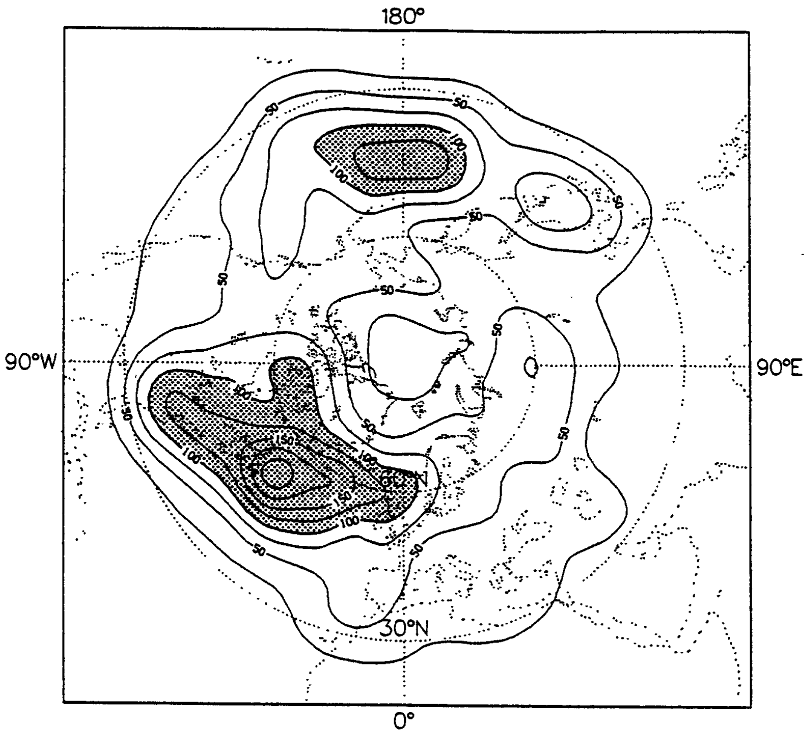


Figure 9(a) Mean 500 hPa height field for the winter of 1985/86. (b) High-pass filtered variance of the 500 hPa height field for the same winter. (c) Low-pass filtered variance.

(b)



(c)

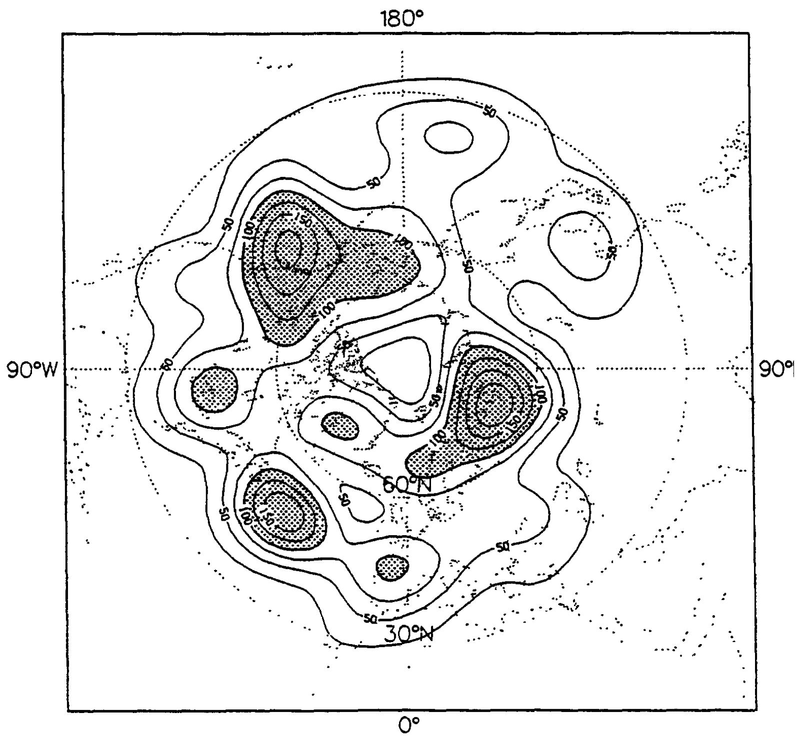


Figure 0. Continued

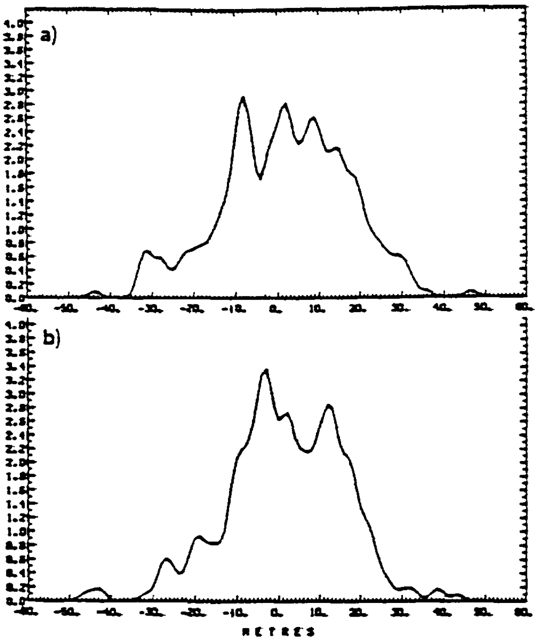


Figure 10. Probability density estimates for the detrended combined amplitude of the first five EOFs derived from two different subsamples: (a)1953–1968; (b)1969–1984.

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