A Quasi-Biennial Oscillation Signal in General Circulation Model Simulations

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The quasi-biennial oscillation (QBO) is a free atmospheric mode that affects the equatorial lower stratosphere. With a quasi-regular frequency, the mean equatorial zonal wind alternates from easterly to westerly regimes. This oscillation is zonally symmetric about the equator, has its largest amplitude in the latitudinal band from 20°S to 20°N, and has a mean period of about 27 months. The QBO appears to originate in the momentum deposition produced by the damping in the stratosphere of equatorial waves excited by diabatic thermal processes in the troposphere. The results of three 10-year simulations obtained with three general circulation models are reported, all of which show the development in the stratosphere of a QBO signal with a period and a spatial propagating structure that are in good agreement with observations without any ad hoc parameterization of equatorial wave forcing. Although the amplitude of the oscillation in the simulations is still less than the observed value, the result is promising for the development of global climate models.

The QBO is the most prominent feature in the variability of the equatorial lower stratospheric circulation. First discovered by Reed (*1*) and by Veryard and Ebdon (*2*), it is characterized by alternating easterly and westerly phases of the mean zonal wind. The amplitude of the QBO is a maximum in the lower stratosphere between 70 and 10 hectopascals (hPa), where the eastward and westward wind regimes repeat at quasi-regular intervals that have varied during the last 30 years between 22 and 34 months with a mean period of 27 months. The peak-to-peak amplitude of the oscillation is ≈30 m/s, almost uniformly distributed in the vertical between 70 and 10 hPa. There is also a phase shift in the QBO signal with a downward propagation of successive regimes at a rate of ≈1 km per month.

The oscillation affects not only the wind and thermal structures at the equator but also the distribution of minor species in the stratosphere. Tolson (*3*) and Hasebe (*4*) have studied the effect of the QBO on the total ozone distribution as measured by the Total Ozone Mapping Spectrometer instrument. The amplitude of the oscillation is of the order of 5 to 8 Dobson units in the latitude band 30°S to 30°N with an extratropical signal that maximizes at high latitudes.

Recent studies show evidence of the extratropical effect of the QBO. Labitzke and Van Loon (*5*) found a statistical correlation between the phase of the equatorial QBO and the development of sudden stratospheric warmings in the Northern Hemisphere winter. Garcia and Solomon (*6*) pointed out the correlation between the minimum ozone column reached during the "ozone hole" buildup in September over Antarctica and the phase of the QBO in the lower stratosphere at the equator.

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The first theories put forward to explain the existence of the QBO were based on the possible existence of biennial cycles of the diabatic forcing in the lower stratosphere or circulation patterns in the troposphere. However, these theories could not account satisfactorily for the irregular period of the oscillation and could not also reproduce the vertical structure.

The only successful theory to date that can explain both the time evolution and the vertical structure of the QBO is based on the momentum transfer of equatorial waves from the troposphere to the stratosphere. Using a mechanistic one-dimensional model, Holton and Lindzen (*7*) demonstrated that the QBO could be an internal oscillation of the atmosphere forced by the damping of vertically propagating Kelvin and Rossby-gravity waves. The easterly phase of the QBO is forced by the absorption of the westward-propagating Rossby-gravity waves with zonal wave number 4 to 5 and a period near 5 days, whereas the westerly phase is produced by eastward-propagating Kelvin waves with zonal wave number 1 and a period near 15 days. These two types of waves have been seen in atmospheric temperature satellite soundings and in ground-based observations. Limb Infrared Monitor of the Stratosphere (LIMS) satellite temperature measurements have been used to identify Kelvin waves with a vertical wavelength of 6 to 10 km (*8*). Such a large wavelength is believed to be determined by the vertical extent of the diabatic heating in the troposphere. Rossby-gravity waves were first discovered in equatorial rawindsonde (*9*) data and identified later with the LIMS data (*10*).

Improvement has been obtained with two-dimensional models that allow a better description of the latitudinal extent of the QBO, its time evolution, and its interaction with the mid-latitude dynamics and upper stratosphere semiannual oscillation (SAO) (*11*). Using a mechanistic stratospheric version of the National Center for Atmospheric Research three-dimensional model, Takahashi and Boville (*12*) have shown that it is possible to develop a realistic QBO, provided that a source of sufficient amplitude is imposed for the Kelvin and Rossby-gravity waves at the lower boundary of the model. Hence, mechanistic three-dimensional models based on the primitive equations can describe the wave-wave interactions that form the basis of the QBO forcing. All of these successful simulations have included an ad hoc wave forcing at the lower boundary of the model.

Tropospheric-stratospheric general circulation models (GCMs) that solve dynamical equations similar to those of the mechanistic models but in addition include comprehensive parameterizations for diabatic processes (such as radiation, convection, precipitation, and latent heat release) should in principle be able to generate a realistic spectrum for the equatorial waves in the troposphere, to model their propagation and dissipation in the lower stratosphere, and hence to produce a QBO signal in the meridional wind structure. Although equatorial Kelvin and Rossby-gravity waves have been diagnosed in the stratospheric simulations of several GCMs (*13, 14*), no evidence has been reported of the existence of a QBO in the model results. This failure to include a QBO is often quoted as a serious weakness of present GCMs and could severely limit their stratospheric predictive capability.

In the first simulation we performed (E42) we used the spectral Emeraude GCM (*15, 16*). This model has 30 levels extending from the ground to about 80 km and uses a progressive vertical hybrid coordinate with 10 sigma levels in the troposphere (below 200 hPa), 15 pressure levels in the stratosphere from 165 hPa up to 1 hPa, and 5 pressure levels in the mesosphere. From the ground up to 35 km it gives a vertical resolution of at least 2 km. With this resolution a large part of the Kelvin wave spectrum can be resolved. Because Rossby-gravity waves have a smaller vertical wavelength (in the range of 2 to 5 km), the model resolution is perhaps the very minimum needed to resolve such waves (*14*).

We used a comprehensive package of physical parameterizations to take account of radiative transfer in the atmosphere, the hydrological cycle, the boundary layer, and convective processes. Results presented in this report were obtained with a T42 triangular horizontal truncation equivalent to a

Gaussian grid with a resolution of 2.8° in latitude and longitude. As part of the Atmospheric Model Intercomparison Program, the model has been integrated over 10 years and the observed monthly mean sea-surface temperatures from January 1979 to December 1988 were used.

The second and third simulations (A21 and A42) were obtained with the climate version of the newly developed Arpège model (*17*). The same 10-year integration was repeated with two different horizontal resolutions. This model retains basically the same physical parameterizations as the Emeraude GCM but allows more flexibility in the choice of resolution and numerical methods to solve the primitive equations. The main differences between the Arpège and the Emeraude GCMs lie in a different formulation of the parameterization of the momentum deposition due to orographically forced gravity waves, with the Arpège code taking into account wave reflection at the tropopause level and using horizontal diffusion, which is a $-K\nabla^6$ formulation, as compared to a bi-Laplacian operator used within Emeraude. The A21 and A42 simulations used nearly the same vertical level spacing as E42 and had triangular horizontal spectral resolutions of 21 and 42, respectively.

The longitude-time diagrams of the anomaly in the zonal component of the wind at 10 hPa averaged over the latitude band from 10°N to 10°S for experiments A21 and A42 are shown in Fig. 1, A and B, respectively. There is a succession of easterly and westerly regimes in the zonal wind anomaly. In the A21 simulation, the oscillation is well established during the first 6 years of the simulation, becomes more erratic from early 1985 to mid-1987, and shows some signs of recovery in 1988. The A42 simulation shows a similar behavior, with a clear signal from the beginning of the simulation up to early 1985. In both simulations, the largest transitions from westerly to easterly regimes occur within 8-month periods and are often followed by 1 year with little change in the amplitude of the anomaly. The bursts of acceleration or deceleration of the zonal wind occur in the first half of 1982, in mid-1983, and at the ends of 1984 and 1987 in experiment A21, and in the second half of 1980 and at the ends of 1982 and 1984 in experiment A42. During these sporadic events, the zonal wind tendencies are of the order of 1 m/s per month. In the observed atmosphere, the zonal wind tendencies are closer to 5 to 10 m/s per month at 10 hPa, but, as in the model, there are periods of rapid change followed by quiet periods. This sporadic behavior is what is expected on the basis of wave breaking theory. Kelvin or Rossby-gravity waves encounter critical levels where they break and deposit momentum. Once the mean flow has been sufficiently altered, the critical level is displaced downward and the momentum deposition ceases.

Although the oscillation in experiments A21 and A42 is far from being periodic in time, a Fourier spectral analysis (Fig. 2, A and B) confirms the existence in both experiments of an oscillation with a period that peaks near 27 months. The existence of this signal is a dominant mode at 10 hPa, whereas it is not significant below 100 hPa and is masked by a strong SAO at and above the stratopause. Although the period of the oscillation is consistent with that of the observed QBO, the zonal wind amplitude is a factor of 4 to 5 below the observed mean values.

A QBO-like signal also occurred in the E42 experiment. The bandpass-filtered amplitude of this wave as a function of latitude and time at 10 hPa is shown in Fig. 3. As in the A21 and A42 experiments, this signal has a larger amplitude during the first half of the simulation. Also noticeable is the latitudinal structure of the wave, with a maximum centered over the equator and secondary maxima at mid-latitudes in both hemispheres. The equatorial QBO extends from 15°S to 20°N, in good agreement with the observed QBO (*1*). As in the A21 and

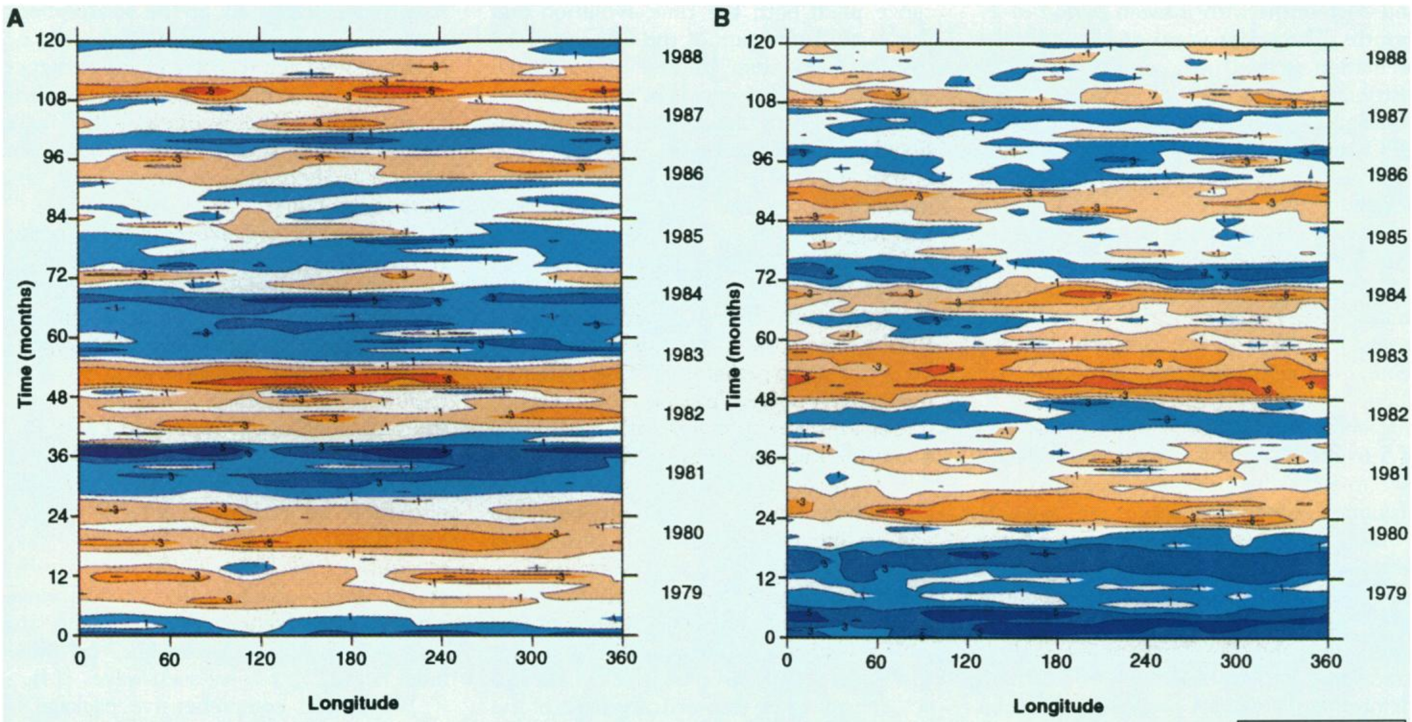

Fig. 1. Longitude-time cross section of the equatorial zonal wind anomaly (zonal wind in meters per second) averaged over the grid points between 10°S and 10°N with the 10-year mean subtracted). (**A**) Outputs from the A21 experiment over the years 1979 to 1988 at the 10-hPa level. A QBO signal arises with maximum intensity during the first 6 years of the integration. (**B**) Outputs from the A42 experiment.

A42 experiments, the amplitude is one quarter of that in the observed QBO. The mid-latitude maxima appear 6 months to 1 year after the equatorial maximum and tend to occur sooner in the Southern Hemisphere than in the Northern Hemisphere. Interestingly, a similar QBO pattern has been observed in the total ozone field (*4*), with equatorial and mid- to high-latitude signals in phase opposition. The total ozone column responds to the meridional circulation driven by the lower stratospheric equatorial QBO with an increase in ozone a few months before the maximum westerlies at 50 hPa. The similarity between the latitudinal patterns found in the modeled wind structure and the observed ozone field suggests that the model has captured some of the important aspects of the oscillation.

The altitude-time evolution of the QBO in the E42 simulation (Fig. 4) is marked by a downward propagation of the wave with a very regular phase velocity of ≈0.8 km per month, a phase speed in good agreement with observations (*18*). A similar vertical propagation was seen in experiments A21 and A42, with consistent numbers for the downward phase velocity, 0.8 and 1.1 km per month, respectively.

In all of the simulations the QBO signal has a detectable amplitude between 6 and 30 hPa, whereas in the atmosphere the oscillation propagates down to the 70-hPa level. This result together with an amplitude for the oscillation in the simulations that is one-quarter of the observed values explain why the equatorial zonal wind does not oscillate between easterly and westerly wind regimes as in the observations except in a thin layer near the 10-hPa level. During the course of the integration the lower stratospheric winds are mostly easterlies, the westerly deceleration being too weak to reverse the flow.

Diagnostics of Kelvin and Rossby-gravity wave amplitudes in the model outputs reveal the existence of easterly Kelvin waves with equatorial zonal wave number 1 and periods between 5 and 10 days. These waves exhibit a broad intensity maximum between 30 and 70 km with a temperature amplitude ranging from 0.5 to 0.8 K and an amplitude for the zonal wind

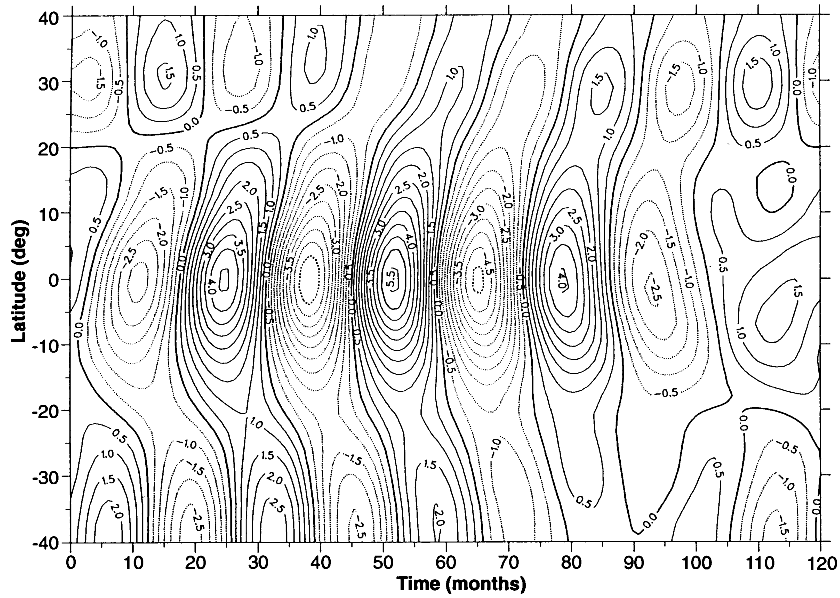

Fig. 3. Longitude-time cross section of the bandpass-filtered zonal wind anomaly at 10 hPa during the course of the E42 integration. In the filtering only the periods between 24 and 32 months were retained. The pattern is composed of a marked equatorial oscillation with an out-of-phase mid-latitude signal.

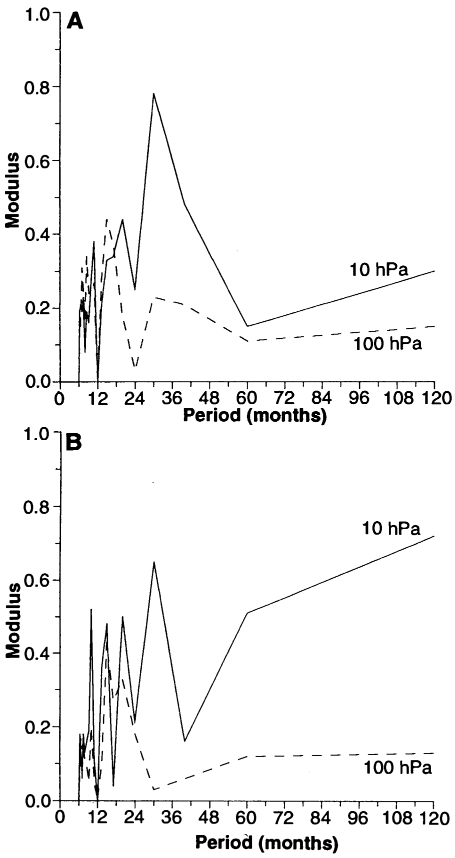

Fig. 2. Power spectra of the mean zonal wind for (**A**) experiment A21 and (**B**) experiment A42, showing a peak at 27 months for the 10-hPa stratospheric level with no significant QBO signal at 100 hPa.

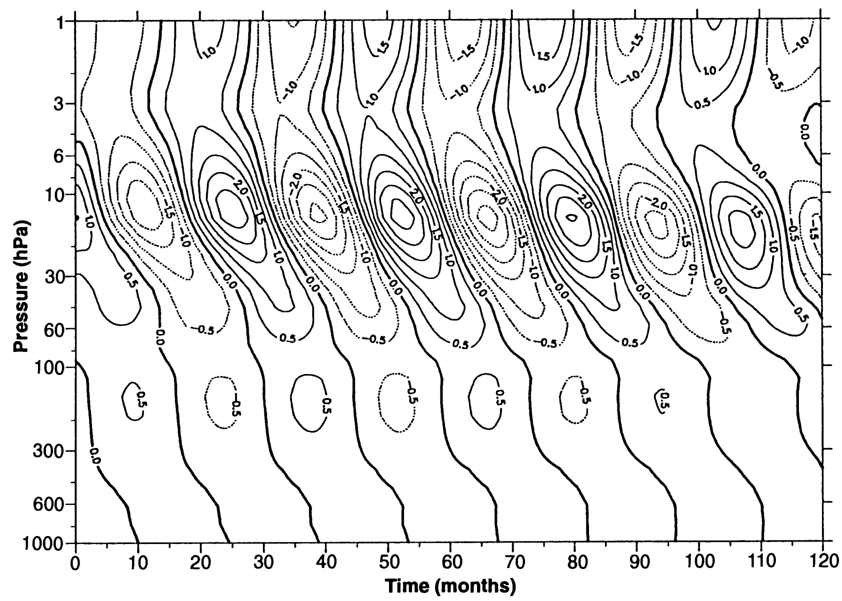

Fig. 4. Time-height cross section of the bandpass-filtered equatorial zonal wind anomaly (averaged over the latitude band from 5°S to 5°N) for experiment E42. The filter used is identical to the one applied in Fig. 3. Clearly shown is the downward propagation of the QBO with a phase velocity of 0.8 km per month.

anomalies of 2 to 8 m/s. These results are consistent with those reported for other GCMs (*13, 14*) and are in the lower bound of measurements. By Eliasen-Palm (EP) flux diagnostics (*19*) it is possible to evaluate the acceleration of the mean zonal flow forced by the wave dissipation. In situations where weak eastward winds prevail in the Emeraude simulation at 10 hPa, the EP flux divergence for wave number 1 maximizes near the level of greater vertical wind shear in the stratosphere at and just above 30 km. The amplitude of the westerly acceleration computed from the EP flux divergence spreads over one or two model levels with values in the range 0.05 to 0.1 m/s per day. Thus, the acceleration produced by the model during transitions to the westerly phase of the QBO can be attributed to the absorption of the Kelvin waves, but a complete reversal of the zonal wind below 10 hPa would require additional forcing or larger absorption of the Kelvin waves in the lower stratosphere.

Rossby-gravity modes are also present in the simulations. A power spectra analysis applied on Emeraude model outputs shows a peak signal for westward-propagating waves with zonal wave number 4 to 5, a period ranging from 2.8 to 7 days, and maximum amplitude for the meridional component of the wind of about 2 to 3 m/s between 100 and 3 hPa. These values fall within the lower range of the observed values. Calculations of the EP flux divergence for these waves show that they exert an easterly acceleration on the mean flow that is broadly distributed over the stratosphere with a maximum of up to 0.1 to 0.2 m/s per day. This drag is balanced by the momentum transport from the mean meridional residual circulation.

We conclude that the Kelvin and Rossby-gravity equatorial waves, which are present in the simulations, are well enough developed to produce a QBO signal with an adequate time period and vertical phase propagation but that an additional forcing is required to produce a QBO that extends into the entire lower stratosphere with an amplitude of several tenths of meters. It is in particular the westerly acceleration that is too weak.

Additional energy for the Rossby-gravity waves could perhaps be obtained by increases in the vertical resolution of the models, but this is unlikely to be sufficient (*14*) and should act rather to increase the easterly winds. The horizontal truncation of the models is clearly adequate to resolve the large-scale Kelvin waves, but small-scale gravity waves with horizontal wavelengths smaller than about 1000 km are not resolved. The breaking of eastward-propagating gravity waves accounts for the westerly deceleration of the mesospheric equatorial jet during the westerly phase of the SAO. Such a mechanism could also be at play for the buildup of the westerly phase of the QBO. In particular, deceleration of the easterly flow by the gravity waves would increase the vertical wind shear and favor the occurrence of critical levels and the damping of Kelvin waves. The present models include a parameterization for the drag due to the breaking of the orographic gravity waves. Other sources of gravity waves, such as vertical wind shear and convection, could play an equally important role in the equatorial stratosphere.

The present study has demonstrated that a QBO signal can develop in GCMs. Further improvement in the representation of unresolved subgrid scale phenomena might be required to produce an oscillation with an amplitude and height comparable to the observed QBO.

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20. The development of the models and the long-term simulations have been sponsored by the Programme Atmosphère Moyenne of the Centre National d'Etudes Spatiales, the Centre National de la Recherche Scientifique, and the Ministère de l'Environnement, by the Alternative Fluorocarbons Environmental Acceptability Study under contract CTR91-29/P91-078, and by the Commission of the European Communities, Environment Program. The Arpège–Integrated Forecast System code is a joint development of the European Center for Medium-Range Weather Forecasts and Météo-France.

18 March 1993; accepted 24 June 1993

Fabrication and Magnetic Properties of Arrays of Metallic Nanowires

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Arrays of ferromagnetic nickel and cobalt nanowires have been fabricated by electrochemical deposition of the metals into templates with nanometer-sized pores prepared by nuclear track etching. These systems display distinctive characteristics because of their one-dimensional microstructure. The preferred magnetization direction is perpendicular to the film plane. Enhanced coercivities as high as 680 oersteds and remnant magnetization up to 90 percent have also been observed.

Artificially structured materials with nanometer-sized entities, such as superlattices and granular solids, have attracted much attention in recent years because of their distinctive properties and potential for technological applications (*1*). Their intricate properties are directly related to the low dimensionality of the entities and can be manipulated through the extra degrees of freedom inherent to their nanostructure. Whereas a bulk solid is three-dimensional, superlattices consist of two-dimensional entities of nanometer thicknesses. By manipulating the layer thickness, the properties of a superlattice can be drastically altered. For example, in magnetic multilayers (such as Fe/Cr and Co/Cu), the spin arrangement of the magnetic layers is dictated by the precise thickness of the nonmagnetic layers (*2, 3*). Equally interesting, in those multilayers where antiferromagnetic alignment of the magnetic layers is realized, giant magnetoresistance has been observed. Granular solids consist of nanometer-sized metallic particles (sometimes referred to as the zero-

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