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ATMOSPHERIC DYNAMICS

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Abstract. American contributions to Atmospheric Dynamics during the period 1983-86 are briefly summarized.

Introduction

Atmospheric Dynamics is the analysis and study of the atmosphere's motion and of the role of this motion in the thermodynamics and chemistry of the atmosphere. As such, it is a large field of study, important to most other fields of atmospheric physics and chemistry. Among the topics in atmospheric sciences for the U.S. National Report to the IUGG, several are intimately associated with atmospheric dynamics (Mesoscale and Severe Storm Meteorology, Operational Numerical Weather Prediction, Boundary Layer Meteorology, and even Cloud Physics), and one is clearly a relatively small subset of dynamics (Atmospheric Columnar Vortices). There can be little hope of presenting a complete report on this field. To begin with we will try to avoid those topics being dealt with in other reports. Finally we will emphasize only a few of the subjects with which we are familiar, and which we feel have been particularly interesting. These topics (which have substantial overlap) are

i) Linear and quasi-linear studies of disturbances
ii) Wave breaking
iii) Long-lived features
iv) Diagnostics for the interactions among disturbances and the mean flow
v) Non-traditional approaches to instability and disturbance growth
vi) Dynamical systems and multiple equilibria.

For each of these topics we will present a brief discussion (which will sometimes have to transcend both the American contributions and the nominal four-year period, 1983-86), and an extensive bibliography of the U.S. contributions. In addition to separate bibliographies for each of the above topics, we have also included a seventh bibliography of some interesting papers which did not fit into the designated categories.

i) Linear and quasi-linear studies of disturbances

Traditional studies of linearized plane waves, normal mode instabilities, and nonlinear studies truncated to the interaction of such disturbances with the mean flow remain the most actively pursued studies. New and interesting results continue to be found. Many of these are dealt with in topics (v) and (iii) above. Work by Salby (1981a, 1981b, 1984a), Lindzen, Straus, and Katz, 1984, Straus, Lindzen, and DaSilva, 1986, Ahlquist (1982, 1985) and others have shown the substantial extent to which simple, stable Rossby waves can still be invoked to explain important atmospheric phenomena. Linear wave theory remains the primary tool for studying tides (Forbes and Garrett, 1979), mountain lee waves (Schoeberl, 1985), and other internal gravity waves (Blumen, 1985). Traditional instability studies still offer useful insights into cyclogenesis (Wang and Barcilon, 1986a, Ioannou and Lindzen, 1986, and many others), clear air turbulence (Rosenthal and Lindzen, 1983a,b, Lindzen and Rosenthal, 1983, Einaudi, et al., 1984) and other phenomena. Wave-mean flow studies remain the primary approach to phenomena like the Quasi-biennial Oscillation (Dunkerton, 1985) and Sudden Warmings (Schoeberl, 1983), and recent studies by Schoeberl and Lindzen, 1984, Nielsen and Schoeberl, 1984, and Schoeberl and Nielsen, 1986, have shown that such truncations often are very adequate approximations to fully non-linear treatments.

ii) Wave breaking

At first, one of the more fascinating aspects of waves and mean flows was their non-interaction (Charney and Drazin, 1961, Eliassen and Palm, 1961, Andrews and McIntyre, 1978). However, it soon became evident that the conditions under which non-interaction breaks down are of great importance in nature (Boyd, 1976, Lindzen, 1973, Andrews and McIntyre, 1978). Among these conditions, is the presence of dissipation. More recently, it was noted that when the wave reached a sufficient amplitude to break, the wave, itself, would provide the dissipation needed for strong interaction. In the case of internal gravity waves, this breaking is clearly associated with the development of convective instability (Lindzen, 1968a,b, Hodges, 1968): the recent renewal of interest in this subject seems to have followed the convenient parameterization of the process by Lindzen, 1981. A substantial amount of work has been done on refining and evaluating this parameterization (Dunkerton and Fritts, 1984, Fritts and Dunkerton, 1984, 1985a,b, Fritts, 1984, Schoeberl, 1983, 1985). Work has also been done on the turbulence budgets associated with breaking gravity waves (Weinstock, 1986), and on applying

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the parameterization to transport problems (Strobel, 1985, Solomon, et al., 1985). Breaking gravity waves were immediately recognized as an important component of the mesospheric momentum budget, and as the main cause of the reversal of the pole to pole temperature gradient at the mesopause (Lindzen, 1973). It had also long been surmised that gravity wave absorption might play an important role in the momentum budget of the troposphere (Lilly, 1972, and more recently, Lindzen, 1985). In the last few years, the breaking gravity wave parameterization has been incorporated into NWP models with substantial positive impact (Palmer, et al., 1986, MacFarlane, 1986), and efforts are currently under way to introduce the parameterization into American models. This topic has arguably provided the best example of the fruitful interaction of atmospheric dynamics, middle atmosphere studies, and weather prediction to date.

It has been argued that Rossby waves may undergo similar breaking (McIntyre and Palmer, 1984), and several studies have analyzed middle atmosphere data for signs of this phenomena (Leovy, et al., 1985), but the situation is still somewhat unclear (Rood, 1985).

iii) Long-lived features

Under this heading we include a number of topics ranging from the climatological stationary waves forced by planetary scale orography and by the relatively fixed regional patterns of heating to the more transient planetary scale disturbances associated with blocking. Various reviews concerning these matters have recently appeared (Held, 1983 for example). In addition a critical review by Lindzen (1986) has recently appeared which questions whether phenomena like blocking are actually long lived. Elaborate data analyses have dealt with these questions (Dole, 1986, Dole and Gordon, 1984 for example).

The importance (potential and actual), of long lived features is fairly self-evident. The climatological stationary waves are the major eddy components of both daily and monthly mean maps. Predicting and understanding these components is essential to forecasting on all time scales. Linear theory has proven reasonably successful in this regard (Alpert, et al., 1983, Jacqmin and Lindzen, 1985, Lin, 1983). An elaborate GCM study confirms the relevance of linear theory as well as pointing out its limitations (Nigam, et al., 1986).

The possibility of teleconnections due to Rossby wave trains excited by distant surface anomalies offers some hope of extended forecast skill. This has led to a large number of theoretical and observational studies (Branstator, 1984, 1985a, 1985b, Wallace and Hsu, 1983, Hsu and Wallace, 1985, Hendon, 1986, Schneider and Watterson, 1984, Paegle and Baker, 1983, among others). Studies of how persistence might be produced by multiple equilibria and by modons have also been popular; these approaches will be discussed separately.

The long period oscillations (30-50 day periods) in the tropics has also excited considerable interest and activity (Lau and Chan, 1985, 1986, among others).

iv) Diagnostics for the interactions among disturbances and the mean flow

The theory of wave energetics and wave/mean flow interaction is undergoing rapid development, building on work related to the Eliassen-Palm flux (Andrews and McIntyre, 1976; Boyd, 1976). Applications to zonally averaged observed (Edmond et al., 1980; Geller et al., 1983; Hartman et al., 1984; Palmer and Hsu, 1983) and simulated flow (Andrews et al., 1983) has given new insight into the role of waves in the general circulation. In particular, a naive interpretation of wave momentum or heat fluxes in isolation is now known to lead to large errors in mean flow tendency.

The E-P diagnostic itself is subject to question in that it is a zonal average of a 3-d process. This has been addressed (Andrews, 1983; Plumb, 1985a,b) but there remains the issue of apportioning the residual forcing and the accuracy of this new tool as well as its interpretation (Robinson, 1986). In this regard results for steady finite amplitude nonlinear solutions are of particular interest (White, 1986; Read, 1985).

The effort to interpret E-P flux diagnostics has focussed renewed attention on atmospheric energetics and is giving rise to generalizations of the original classical work of Lorenz (1955) to take account of the noninteraction limit (Plumb, 1983; White, ibid).

v) Non-traditional approaches to instability and disturbance growth

Non-traditional instability theory has recently advanced on a number of fronts. Most fundamentally, the general formulation of criteria for instability by Arnold (1965) and Blumen (1968) has been extended by McIntyre et al., 1986; Holm et al., 1984 and Andrews 1984a,b. These theories produce integral bounds which subsume the classical instability theorems of Rayleigh and Fjortoft but also go beyond them to bound the increase of disturbance energy in flows without exponential instability (Farrell, 1982).

It is now recognized that the zonal concentration of variance at synoptic scale in storm tracks requires a generalization of temporal normal mode theory to zonally asymmetric flow. This generalization raises new issues both in the theory of instability and the interpretation of model results which are as yet unresolved. Progress has been made in model work on the instability of climatological flows (Frederiksen, 1983; Simmons et al., 1983; Branstator, 1985), in nonzonal instability theory (Niehaus, 1980; Lindzen et al., 1983; Pierrehumbert, 1984; Merkine and Balgovind, 1983) and in orographically modified instability (Pierrehumbert, 1985; Speranza et al., 1985; Smith, 1986). Extending instability theory to zonally varying flows has helped to widen its scope to include alternatives to temporal normal modes including spatial and the mixed pulse asymptotic description (Merkine, 1977; Farrell, 1983). In particular the dependence of non-zonal flow instability on the existence of absolute instability has raised an important new issue for the theory.

Complementing the advances in instability theory has been interest in disturbance development outside the purvue of exponential growth, including the dynamics associated with straining fields. General integral bounds (Pierrehumbert, 1983; Zeng, 1983; Henrotay, 1983) and observational studies (Hoskins et al., 1983) as well as model studies (Shutts, 1983; Farrell, 1985) have been instrumental in extending the concept of development to include processes associated with waves which are not of normal mode form. The role of this transient growth phenomena in the energetics of waves and the general circulation and the relation it bears to traditional normal mode growth is not well understood at this time.

vi) Dynamical systems and multiple equilibria

The theory of nonlinear processes has advanced, especially the study of local (Malguzzi and Malanotte-Rizzoli, 1984; Williams and Yamagata, 1984a; Verkley, 1984) and global nonlinear modes (Mitchell and Derome, 1983; Read, 1985) and their origin (Pierrehumbert and Malguzzi, 1984; Hou and Farrell, 1986). Multiple equilibrium theory has been explored using less highly truncated models than Charney and DeVore (1979) to explain blocking and index cycles (Legras and Ghil, 1985) and generalized to baroclinic flows (Rambaldi and Mo, 1984; Reinhold and Pierrehumbert, 1982). These ideas have been critically reviewed (Held, 1983; Tung and Rosenthal, 1985) and their relevance to the atmosphere remains an open question.

Dynamical systems theory has come to be identified with the fascinating behavior of nonlinear model and physical systems with attractor phase spaces of low and often fractal, dimension. As the equations of motion governing fluid flow are highly nonlinear, it is natural that truncated models of these systems should provide a rich source of examples of such behavior beginning with the now classic work of Lorenz (1963). That the dimensionality could be reduced by the inherent dynamics was demonstrated by Pedlosky and Frenzen (1980) in a dissipative, weakly supercritical two layer model. Since then the application of techniques associated with dynamical systems theory to problems related to vacillation in annulus experiments has been rapid (Chou and Loesch, 1986; Weng, Barcilon and Magnan, 1986; Hart, 1984). While the underlying phenomena of rapid divergence of trajectories in the phase space of nonlinear systems is likely to be robust in its relation to the predictability problem, the original motivation of Lorenz, it remains to show that the atmosphere has important dynamics confined to attractors of low enough dimension to justify application of these techniques. Indeed, estimation of dimension in an annulus exhibiting geostrophic turbulence yielded attractors of dimension near 10 (Guckenheimer and Buzyna, 1983).

Conclusion.

It should be regarded a sign of vitality in the field of atmospheric dynamics that the work of the past few years has raised at least as many new issues as it has provided solutions. Areas in which advances can be expected include the use of momentum transport by breaking gravity waves in NWP models and the understanding of storm track structure proceeding from studies of local instability of asymmetric flows. Resolution of the problem of wave/mean flow interaction and the difficulty of formulating an unambiguous energy cycle remain as goals for the future.

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ii) Wave breaking

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