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INSTABILITY STUDIES OF MONSOON AND EQUATORIAL FLOWS

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CERTIFICATE

I hereby declare that the work presented in this thesis is original and has not formed the basis for the award of any degree or diploma by any University or Institution.

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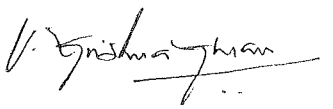

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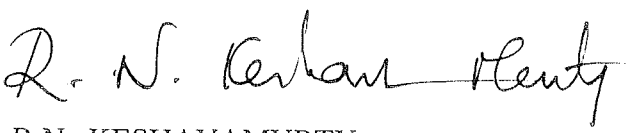

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INSTABILITY STUDIES OF MONSOON AND EQUATORIAL FLOWS

CONTENTS

ABSTRACT

The southwest summer monsoon over India is characterized by a strong westerly current in the lower levels and a strong easterly current in the upper levels. Within this season, there are various disturbances of horizontal scale of 2000 - 3000 km and time scale of a few days which form and decay. Among these, the monsoon depressions which form over the North Bay of Bengal (Head Bay) and the cyclonic onset vortex which forms over the south-central Arabian Sea are the major disturbances which bring heavy rainfall to the Indian subcontinent. There are also mid-tropospheric cyclones over western India. These are the important components of the southwest summer monsoon. There are also fast westward propagating waves in the monsoon upper troposphere. The questions related to the genesis, growth, the length and time scales of these disturbances, their three dimensional structure and the need to forecast them on the medium range time scale, are some of the very challenging problems in the theoretical and modelling studies of monsoon dynamics.

There have been many studies towards understanding the formation of monsoon depressions in the frame work of dry as well as moist linear models. Several of the shortcomings of the linear dry models were mainly attributed to the non-inclusion of cumulus heating.

Then emerged the second class of moist linear models, by incorporating the feedback effect of moist convection. The linear instability studies pertaining to the growth of the onset vortex are only a few. These models were mainly without considering the cumulus heating.

All the previous studies were mainly confined to quasi-geostrophic models. The disturbances like the onset vortex and the monsoon depression are equatorial phenomena and one needs to examine them using the complete primitive equation model to incorporate nongeostrophic effects.

The impact of the upper tropospheric wave disturbances on weather at the lower levels has not been clearly understood. From observations, there is some evidence to believe that these disturbances may propagate downwards and may act as triggering mechanisms for the genesis of monsoon disturbances. This aspect has not been studied carefully.

The main shortcoming of the instability models of the synoptic scale disturbances may be attributed to the use of linear models. Quite recent nonlinear studies of idealized systems suggest that the three-dimensional structure of the most unstable mode is likely to change as the intensity of the disturbance becomes sufficiently large. The need to study the nonlinear evolution of these disturbances need not be stressed upon.

There is some observational evidence that monsoon zonal flow in the equatorial region may satisfy the condition for inertial instability. We have, thus examined the possibility of symmetric instability of the monsoon zonal flows.

In the tropical atmosphere, observations show that the subseasonal oscillation on the time scale of 30-50 days is one of the dominant modes. When this equatorial oscillation comes over the monsoon region, it propagates northward with a speed of approximately 1^0 latitude per day. We have examined the northward propagation of the 30-50 day oscillation in the framework of an

analytical model.

We propose to study the detailed stability analysis of the monsoon and equatorial flows with a view to understand the physical mechanisms of growth and the evolution of the important synoptic scale disturbances using both linear as well as nonlinear models. A multi-level primitive equation linear model and a global spectral nonlinear model are used to understand the genesis, time and length scale and the structure of the onset vortex and the monsoon depression. The contents of this thesis are divided into seven chapters.

Chapter I gives a brief description of the important observational features of the synoptic scale monsoon disturbances and the low frequency oscillation of the monsoon. In this Chapter a brief review of the instability mechanisms with a specific reference to the classic models, is given. Important instability studies pertaining to the growth of these disturbances in the Indian summer monsoon are briefly outlined. A brief review of the equatorial symmetric instability and also of the 30-50 day oscillation of the monsoon is given. This Chapter closes with a discussion of the aim and scope of the thesis.

Chapter II deals with the stability analysis of the mean basic monsoon flow with vertical shear and in the presence of cumulus heating using a complete multi-level primitive equation model. Three cumulus heating formulations used for this study have been discussed. The multi-level primitive equation model and the quasi-geostrophic model which were used to highlight the nongeostrophic effects in the growth of monsoon disturbances are discussed in detail. The important results of this study are also

summarized. The results indicate that the lower tropospheric monsoon disturbances may grow by baroclinic instability under the influence of cumulus heating and upper tropospheric easterly waves may grow by baroclinic instability. The nongeostrophic effects apparently have only a secondary role in the growth of these disturbances.

Chapter III deals with the study of vertical (downward) propagation of the upper tropospheric modes in the monsoon region. The detailed formulation of the multi-level quasi-geostrophic model used in this study is discussed. The theoretical formulation and the derivation of an expression for the vertical refractive index with the mean monsoon basic state are given and a case study with actual observations is included. The theoretical investigation shows that there is a possibility of vertical (downward) propagation of the upper tropospheric unstable mode in the monsoon region. Observations also show downward propagation of a disturbance.

Chapter IV deals with the nonlinear studies of the monsoon depression. A nonlinear spectral model has been used for this study. A brief description of the model and the description of the experiment carried out with the model are given. Energetics calculations of the model disturbance are outlined here. We have shown, in quite a new approach, the nonlinear evolution of this disturbance using a five level global spectral model. We have simulated a monsoon disturbance around 23^0N with a realistic structure like the observed disturbance by choosing an anti-symmetric heating distribution. The simulated monsoon depression intensifies in the presence of the cumulus convection. The

energetics calculations reveal that baroclinic energy exchange is the primary exchange process and cumulus heating is the driving force for the generation of available potential energy.

Chapter V deals with the linear and nonlinear studies of the monsoon onset vortex. For the linear studies, a three-level primitive equation model with a simple form of cumulus heating has been considered. The detailed formulation of the three-level model is discussed extensively in this chapter. For the study of the nonlinear evolution of the onset vortex, a nonlinear global spectral model with a parameterized cumulus heating has been used. The details of the experiments with the model are outlined in this chapter. The two experiments carried out with the model, first by choosing a small heating region and second by choosing a large heating region are also described. The detailed energetics calculations of the simulated onset vortex are also described.

The important results using the linear model are the appearance of the two upper tropospheric growing modes one with amplitude centered around the equatorial region and one with amplitude centered around 20^0N with wavelengths around 2000-3000 km. These modes move westwards with speeds around 15-25 m s^{-1}. These modes have similar characteristics of the observed upper tropospheric easterly modes in the monsoon region. In the lower troposphere, we found two modes one with amplitude centered around the equatorial region and the other with amplitude centered around 10^0N. The second lower tropospheric mode has the observed characteristics of the monsoon onset vortex with a wavelength of around 3000-4000 km.

With a nonlinear global spectral model, a vortex resembling the monsoon onset vortex has been generated around 13^0N-16^0N. It can be seen from the structure of various fields that the vortex has cyclonic flows in the lower levels and anticyclonic flows in the upper levels. All the fields show the characteristics similar to those of the observed onset vortex. The growth of this disturbance becomes very much pronounced in the presence of cumulus heating. The detailed energy conversions show that the barotropic energy exchange is important from Day 1 to Day 3. The calculations also show that the baroclinic energy exchange becomes quite prominent as compared to the barotropic energy exchange from Day 4 onwards, illustrating the importance of baroclinic energy conversion in the presence of cumulus heating.

Chapter VI deals with the study of symmetric instability of equatorial monsoon flows. A brief review of the inertial instability in the equatorial region is given. The important observational aspects in the monsoon region are also highlighted in this chapter. The details of the theoretical analysis with the zonally symmetric perturbation equations are given. The results of the stability analysis are outlined. Investigation of the meridional circulation and its fluctuations with the zonally symmetric perturbation equations are described. The results of the stability analysis in the dry as well as moist model reveal that there are unstable and neutral equatorial eigen modes in the monsoon region. The unstable modes have periods around 1 to 2 days with doubling times of around 1 to 2 days. The structure of these modes exhibits cellular structure with horizontal dimension around

6^0 latitude and with maximum amplitude centered in the lower and middle troposphere. Two classes of neutral modes were found, one having a Hadley cell like structure with respect to the equator and the other having ascent near the equator and descent in both the hemispheres. Thus, we have shown that zonal flows in the monsoon region exhibit symmetric instability.

The solution of the zonally symmetric perturbation equations with a fluctuating heat source of 40 days shows a meridional circulation in the equatorial region with ascending motion over the northern latitudes and descending motion over the southern latitudes similar to the observed monsoon cell. The investigation reveals that fluctuating equatorial heat sources induce fluctuating monsoon meridional circulation; however there does not appear to be any preferred period in the range between 5 and 40 days.

Chapter VII deals with the theoretical investigation of the northward propagation of the 30-50 day oscillation in the Indian monsoon region. This Chapter gives a brief overview of the observational and theoretical aspects of this oscillation in the tropical as well as Indian monsoon region.

We have derived expressions for the meridional refractive index of the 30-50 day mode with a simple cumulus heating and using a two level analytical model. In the monsoon region, we obtained a 'complex refractive index' which implies northward propagation of this equatorial oscillation in the Indian monsoon region. We have also derived an analytical expression for the phase speed of this oscillation using a highly simplified system of equations. The calculations with the theoretical expressions

show a reasonable value for the phase speed agreeing with observations. The northward movement is primarily controlled by the basic wind profile and cumulus heating.

The most important achievements and conclusions of this thesis are :

(i) In a combined barotropic-baroclinic instability analysis including nongeostrophic effects as well as in a simple baroclinic instability analysis of monsoon flows, we obtained westward propagating upper tropospheric growing modes resembling the observed easterly waves.

We have theoretically shown that conditions are favourable for the downward propagation of these modes. We have also seen such downward propagation in observations.

When the effect of cumulus convection is added in, some lower tropospheric growing modes are obtained. But these do not show a preferred scale.

(ii) Using a nonlinear global spectral model and by choosing an antisymmetric heating distribution, a monsoon disturbance around 23^0N with a realistic structure like the observed disturbance is simulated. In the presence of cumulus heating , a pronounced growth of this simulated disturbance is seen. The energetics calculations of the simulated disturbance show that baroclinic energy exchange is the primary exchange process in the presence of cumulus heating. Barotropic conversion is rather small.

(iii) In a combined barotropic-baroclinic instability analysis with cumulus heating and including nongeostrophic effects, a lower tropospheric mode resembling the onset vortex is

generated.

In a nonlinear study using a nonlinear global spectral model, north-south heating contrast generates an onset vortex which grows by cumulus heating. The vortex has cyclonic flow in the lower levels and anticyclonic flow in the upper levels. It has the structure of an equatorial Rossby wave. Barotropic exchange of energy shows positive exchange from Day 1 to Day 3 and later on the baroclinic energy conversion in the presence of cumulus heating becomes quite conspicuous illustrating the prominence of cumulus heating.

(iv) Zonal flows in the monsoon region also exhibit symmetric instability. Fluctuating equatorial heat sources induce fluctuating monsoon meridional circulation ; however there does not appear to be any preferred period.

(v) We have analytically derived an expression for the meridional refractive index for the northward propagation of the 30-50 day mode in the Indian monsoon region. Our results indicate that northward movement of this mode in the monsoon region is primarily controlled by the mean basic flows and cumulus heating. Northward speeds of a couple of metres per second were obtained.