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Report of a workshop for the Winter Monsoon Experiment, 14-15 June 1982, Monterey, California

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REPORT OF A WORKSHOP FOR
THE WINTER MONSOON EXPERIMENT,
14-15 JUNE 1982, MONTEREY, CALIFORNIA

by

C.-P. Chang and P. J. Webster,
editors

March 1983

Technical Report

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NAVAL POSTGRADUATE SCHOOL
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This is a report for the Winter MONEX Workshop held at the Naval Postgraduate School, Monterey, California, in June 14-15, 1982.

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1. INTRODUCTION

Since the field phase of the Winter Monsoon Experiment (Winter MONEX: December 1978 - March 1979), considerable effort has been expended in collecting and checking data in order to create a consistent data set for research purposes. With this task completed research has been undertaken utilizing the data set in diagnostic studies and in parallel theoretical and modelling endeavors. Preliminary results have been presented at two international conferences (Tallahassee, January 1981 and Denpasar, Indonesia, October 1981*).

The U.S. National Academy of Science MONEX Panel at their 2-3 June 1981 meeting saw merit in national scale "workshops" for each of the components of MONEX. It was felt that the workshop concept would allow a degree of discussion on specific topics and problems and the identification of specific areas of research which may have been overlooked and which would be difficult to address at an international conference. That is, the workshops were to provide a venue where current progress by the U.S. scientific community could be established and directions for future research suggested.

The following pages constitute a report on the Winter Monsoon Experiment workshop held at the Naval Postgraduate School, Monterey, California, June 14-15, 1982.

The agenda for the workshop is attached in Appendix A. Four working groups were established; two for the Large Scale Flow and two for the Small Scale Flow. Results from each of the four groups are given below as:

Section 2: Large Scale Motion (Cold Surge)

Section 3: Large Scale Motion (Forcing)

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*(1) "International Conference on Early Results of FGGE and Large-Scale Aspect of Its Monsoon Experiments", Tallahassee, Florida, Jan 12-17, 1981.

(2) "International Conference of the Scientific Results of the Monsoon Experiment", Denpasar, Bali, Indonesia, Oct 26-30, 1981.

Section 4: Small Scale Motion (Regional-Synoptic)

Section 5: Clouds and Precipitation

A list of attendees is attached in Appendix B. A broad representation of U.S. institutions engaged in winter monsoon research was present. In addition, visitors from four monsoon area countries were able to accept invitations to attend the workshop.

Finally, it should be pointed out that many of the research results presented at the workshop are of a preliminary nature. Where possible, a refereed journal reference is given. In many cases only a conference proceedings reference or an informal reference to a discussion at the workshop is possible. For further information regarding the status of the research discussed under the latter two forms of reference, we suggest that the reader contact the worker in question.

Finally we would like to acknowledge the support of the Chairman of the MONEX Panel, Prof. J. A. Young, the members of the Panel, the National Academy of Science, and the National Science Foundation in making the workshop possible.

2. LARGE SCALE MOTION (COLD SURGE)

2.1 Planetary scale interactions associated with cold surges

During cold surges the planetary-scale circulation over the Asia-Pacific region appears to undergo significant short term changes on a time scale of a few days. This phenomenon has been studied independently by two research groups at the Naval Postgraduate School and Colorado State University.

The studies by Chang and Lau (1980, 1982) and Lau et al. (1982) using both pre-MONEX ans MONEX data, showed that in general several major midlatitude and tropical circulation components vary in a coherent way during surge periods. As the surge develops, the upper tropospheric jet streak near Japan, the local Hadley circulation over East Asia and the upper-tropospheric divergent outflow over the maritime continent all strengthen steadily and continue for several days. The Walker circulations over the equatorial Pacific and Indian Ocean are also enhanced in the same time frame.

Chang and Lau suggested the following sequence of events to explain the observed circulation changes. Initially, intense baroclinic development in the East Asia midlatitudes strengthens the local Hadley circulation and leads to rapid, equatorward cold air surges in the lower troposphere. The cold surges cause an enhancement of the cyclonic disturbances and their associated convection in the equatorial trough region. The flare-up of convection and latent heat release enhances the tropical upward motion and further strengthens the East Asia local Hadley circulation. At the entrance region of the jet streak near Japan, the ageostrophic Coriolis torque exerted by the enhanced local Hadley circulation throughout the surge period accounts for a large part of the local zonal wind acceleration. On the other hand, the downstream acceleration and an observed eastward progression of the jet maximum are largely due to the effect of increased momentum flux conver-

gence from the strongly baroclinic disturbance that initiated the surge in the first place.

The proposed explanation for the strengthening of the local East Asia Hadley circulation was consistent with the analysis of Winter MONEX data by Boyle (1982), who showed that the 200 mb southerly divergent wind is significantly correlated with the surface northerly divergent wind within ±48 h, with a maximum correlation at the 36 to 48 h lags. This suggests that the maximal enhancement of the upper level return flow occurs 36-48 h after the occurrence of maximum surge winds.

Chang and Lau (1982) also showed that during inactive (monsoon break) periods the midlatitude circulation components all exhibit reversed changes from those of the active (surge) periods, while the variations in the tropics are less coherent although still showing reversed tendencies. This contrast in the degree of organization of the tropical responses between the active and inactive periods appears to suggest that during winter, the tropics are forced by the midlatitudes rather than vice versa, at least over East Asia and the Pacific.

During northern summer, Love (1982) and Sikka and Gray (1982a, b) observed short-term enhancements of the southern hemispheric jet stream near Australia which are in-phase with enhanced tropical convection in the northern tropics. Thus it appears that the tropical convection influences the winter hemispheric jet through enhanced Hadley circulation in both northern and southern hemispheres.

Love, Sikka and Gray further showed that large-scale cold surges from the winter hemisphere exert a cross-equatorial influence on the summer hemispheric ITCZ, often leading to tropical cyclogenesis in the summer-hemispheric western Pacific and Indian Ocean. They suggested that the cross-equatorial surges would lead to pressure rises of around 1-2 mb on a scale of 20°-30° longitude by 10° latitude in the summer tropics. The westerly monsoon winds there appear to adjust to this mass forcing by undergoing a "down the pressure gradient" acceleration

through a deep layer of the lower atmosphere (surface to 400-500 mb) which often results in tropical cyclone genesis.

2.2 Initiation of cold surges in the midlatitudes

Boyle (1982) carried out case studies of the initiation and development of cold surges occurring over Eastern Asia for the months of December 1974 and December 1978. The three-dimensional midlatitude circulation patterns of the surge events occurring during these two months has been carefully analyzed, along with the larger scale circulation in which they were imbedded. December 1974 was chosen since it was a month of very intense cold surges, while December 1978 (Phase I of Winter MONEX) was a month characterized by cold surges weaker than normal.

A quasi-stationary midlatitude long-wave ridge-trough pair at 300 mb appears to provide the background for cold surges. The ridge is over the continent which supports the Siberian anticyclone at the surface. The trough is normally in the vicinity of Japan providing a confluence zone near the eastern Asia coast.

The results of individual surge events showed that they are initiated by strong subsidence in the Yellow Sea/East China Sea region due to baroclinic intensification of short waves propagating around the long-wave trough. Time-height sections clearly demonstrate that the divergent outflow at the surface provides an impetus for the surge of cold air southward. The descent is part of a direct circulation in the entrance region of the East Asia jet over Japan. The ascent region is generally less well defined with respect to geographical location but is about 10° latitude to the south of the descent. Thus the East Asian surges appear to release the zonal available potential energy from the "cold pole" (lowest 1000-500 mb thickness) in proximity to the cold air source region.

The upper level short wave (maximum amplitude around 500 mb) which initiates

the subsidence in the Yellow Sea area usually triggers cyclogenesis off the East Asia coast. The cyclone is a transient feature and moves quickly to the east toward the position of the Aleutian low while deepening rapidly. It is significant that as the cyclone/anticyclone ascent/descent couplet moves to the west a separate and distinct subsidence region remains in the Yellow Sea area. In the time series for the Yellow Sea area there are two distinct maxima in the descent. The first is associated with the developing cyclone; the second is separate from the cyclogenesis and is as intense as the first. Thus there appears to be both a transient and quasi-stationary component to the subsidence which is forcing the cold air surges. The flow of cold air southward is not just the thrust of cold advection to the rear of a strong cyclone but is linked to subsidence forced by the long wave pattern.

Another mechanism for the initiation of surges was proposed by Webster (1981), who suggested that the cold surge is an ageostrophic compensation of the climatological monsoon circulation to the influence of midlatitude events. These high latitude events take the form of migrating troughs, which upon entering the confluence region of the climatological jet increase the convergence of westerly momentum causing a rapid westerly acceleration. The secondary circulations corresponding to the increase in intensity of the jet are thermally direct in the entrance region and indirect in the exit region.

These circulations migrate following the jet stream and upon crossing the East Asia coast the direct secondary circulation enhances the monsoon cell. The surface wind develops a strong northerly isallobaric component, producing the surge, as pressures rise over the land and fall over the South China Sea.

2.3 Dynamics of influences of cold surges in low latitudes

The very rapid progression of cold surges toward the equatorial latitudes on a large spatial scale and the very short time scale of the midlatitude-tropical interaction are intriguing phenomena. Lim and Chang (1981) hypothesized that the fast propagation at low latitudes is due to the transient motion induced by an initially unbalanced pressure surge in the midlatitudes. They used a linearized shallow water equation model with an internal wave depth scale on an equatorial beta-plane to study the dynamic response of the tropical atmosphere to such a surge forcing. The initial value problem approach leads to solutions consisting of transient motions, and groups of equatorial wave modes. After an initial period of gravity-wave type motions with pronounced cross-isobaric northerly winds, the response separates out into a slowly westward drifting main group and some eastward moving disturbances. Several features of the main group of responses closely resemble the observed flow pattern of the northeast monsoon region, such as the northeasterly wind streak over the South China Sea during cold surges, the mean winter condition of a cyclonic shear trough extending from Borneo to the Philippines, and the cyclonic circulation near the northern Borneo coast. Lim and Chang proposed that the observed flow pattern of the northeast monsoon region may therefore be regarded as being forced and maintained by successive mid-latitude pressure surges. Following each intensification of the continental anticyclone, characteristic features of the flow pattern, such as the northeasterly wind streak and cyclonic circulation over northern Borneo coast, strengthen in response.

The cyclogenesis in the equatorial latitudes due to surge forcing was also modeled numerically by Love (1982) using shallow water equations with spherical geometry. Love's numerical experiments also showed that external mode simulations, with mass field forcing in the winter hemisphere, most closely match the short time

scale of opposite hemisphere response which is observed with the data. The induced wind field perturbations act to increase the westerly wind in equatorial regions, then planetary scale wind and mass perturbations are established in the summer hemisphere.

Lau and Lim (1982) further incorporated an equatorial heat source in the shallow water equatorial beta plane model to obtain solutions of large-scale thermally driven motions. They found that, when coupled with the equatorial heat source, the sudden cooling of the lower troposphere over a localized area in the subtropics gives rise to northeasterly wind surges and Walker and Hadley circulation variations reminiscent of periods of strong cold surges.

Chang and Lim (1982), in an analysis of the linear response to steady equatorial forcing in a constant mean wind, found that the observed characteristics of seasonal mean Walker circulations can be obtained only in a westerly mean flow even though the equatorial mean flow is normally easterly. They argued that the steady forcing in mean westerlies is equivalent to a transient forcing of Walker circulations in weak easterlies since the Rossby wave group response to the transient forcing always propagates westward relative to mean flow. They therefore hypothesized that the frequent enhancements of Walker circulations due to cold surges as observed by Chang and Lau (1980, 1982) must play an important role in the observed time-mean structure of Walker circulations.

2.4 Interannual variability of cold surges

The large-scale divergence pattern at 850 mb and 200 mb during the Winter MONEX of 1978-79 is considerably different from that of the earlier years of the 1970's. The main large-scale equatorial rising motion in 1978-79 is over the equatorial south-central Pacific rather than the "normal" position of the equatorial maritime

continent. This was also a season of abnormally weak cold surges compared to the normal intensity of surges (Chang and Lau, 1982; Murakami and Sumi, 1982a, b; Lau et al., 1982).

In a study of the short-term teleconnection during Winter MONEX, Lau et al. (1982) compared the cold surges and associated planetary scale circulation changes in 1978-1979 with those of 1973-1976. They found that the local Hadley circulation over East Asia in 1973-1976 was replaced by two local direct cells. The main overturning connects the equatorial central Pacific and northern China, while the secondary one connects the maritime continent and northern China. They also noted a reduction in the coherent out-of-phase variation between the East and West Asia jets at 200 mb reported by Chang and Lau (1980, 1982), and a more coherent variation between the East Asia jet and a secondary subtropical jet over Hawaii. Lau et al. (1982) speculated that the remoteness of the main equatorial convective region (as indicated by the upper divergence and lower convergence centers) from the cold Asian continent is responsible for the weakness of the surge intensity in 1978-1979.

Looking for interannual variations in the upstream region of surges, Boyle (1982) compared the midlatitude circulations between December 1974, a strong surge month, and December 1978 of Winter MONEX.

The monthly mean results showed the key role played by the long-wave trough and ridge positions at upper levels (300 mb) in determining the amplitude of the cold surges. December 1974 had a prominent mean ridge along 60°E at 50°N and a strong confluence zone beginning at around 120°E to the west of the long-wave trough position at 140°E. Boyle showed that this ridge provided upper level support to the Siberian anticyclone which was more intense than normal in 1974. The monthly mean fields for December 1978 show only a very modest broad ridge over Eastern Asia, with no prominent zone of confluence and a mean trough position well

to the east of the coast at 145°E. Thus it appears that the difference in basic flow in the higher latitude may also be used to explain the variation in surge activities between the two seasons.

Krishnamurti et al. (1982) analyzed the monthly mean flows at 200 mb and 850 mb for a ten year period from 1965-1974. The northeast monsoon wind field shows a low-frequency variation on the time scale of the Southern Oscillation. They suggested that there is a strong connection between the anomalies in the monsoon circulation and the Southern Oscillation. Thus it is possible that this connection is related to the interannual variation in the strength of cold surges.

2.5 Future research

Most of the observational studies of the planetary scale motions used the MONEX quick look or Level IIb data. Several Level IIIb data sets are now available. These data sets should be used to re-examine the large scale events leading to cold surges and the associated short-term teleconnection patterns. In a numerical experiment, Krishnamurti used a IIIb data set as the first guess to reanalyze the MONEX data set therefore essentially merging the two into an enhanced Level IIIb MONEX data set. Such an approach probably extracts the maximum benefits from the available data sets. The study of the large-scale circulation can also be aided by using satellite IR and precipitation data to examine the large-scale convection patterns. Digitized satellite data from TIROS N and GMS are now available from D. Martin of the University of Wisconsin and M. Murakami of Japan's Meteorological Research Institute, respectively.

While the Winter MONEX region often has the most intense cold surges due to the Eurasian continent mass and other terrain effects such as the Tibetan Plateau, surges also occur regularly in several other parts of the world. For example, surges in the winter hemisphere towards lower latitudes, and even penetrating into

the summer hemisphere, occur frequently in America, Australia and the Indian Ocean. The initiation, planetary-scale flow changes, and downstream influences of these surges should be studied. In fact, in any earlier case study of an anomalously warm three-day period over the Caribbean in February 1964, Bosart (1973) has suggested the possibility of a midlatitude-tropical interaction through cold surges and the local Hadley circulation there. Comparisons of surges in these different regions with those in East Asia would be valuable in understanding the surge mechanisms and effects in different regions.

Another primary research topic related to the downstream influence of surges is to separate the influences of normal Summer ICTZ convection on opposite hemisphere sub-tropical jet (STJ) enhancement from such enhancement that results from the winter hemisphere 1-3 days scale cold surge influences (of Summer ITCZ convection and upper level cross-equator feedback flow to the STJ).

Despite the Winter MONEX, high-frequency three-dimensional data coverage of cold surges in the tropics is still lacking. Studies of the dynamics of the surges in the tropics therefore remain inadequate even though some progress has been made. Theoretical studies of surges and responses in the tropics have been limited to the use of shallow water equation models. To properly treat the vertical structure and effects of mean wind shear, three-dimensional models will be required. Observational knowledge of the three-dimensional structure of surges in adequate time resolution is also needed to further the theoretical studies.

The observational and theoretical results obtained so far suggest that the dynamics governing cold surges may be quite different in the midlatitudes and tropics. In the midlatitudes, the time scale is comparable to that of advection such that quasi-geostrophic dynamics is basically adequate to describe the motion. In the tropics the time scale is much shorter, suggesting the possibility of gravity

wave dynamics and the importance of mesoscale convection. Only very limited observational and theoretical studies addressing the basic dynamics of the surges have been carried out, and their results are subject to the many assumptions and hypotheses used. Substantially more work needs to be done, especially in data analysis, to obtain a more definitive picture of the basic dynamical processes in the tropics.

Numerical weather prediction experiments of cold surges in the tropics have not been carried out by any known research group. This is a particularly difficult problem in view of the broad area and the short time scale involved. However, numerical models are necessary to study the effects of vertical and horizontal shear and the complex terrain in the Winter MONEX region. Numerical experiments of the midlatitude baroclinic events associated with cold surges would be easier and are implied in operational global NWP forecasts.

Detailed analysis of these operational global NWP outputs should be helpful in studying the midlatitude cold surge processes. On the other hand, dedicated numerical experiments designed for cold surge research are required to elucidate the various mechanisms of cold surges at all latitudes.

The equatorward surge winds are confined to the lower layer of the troposphere in the tropics, and the surges interact with the convection activity in the equatorial trough region. Therefore the planetary boundary layer processes must be important. However, very little work has been done on the planetary boundary layer structure, despite the fact that the Winter MONEX data set includes several forms of boundary layer data. These data should be analyzed to study the important boundary layer processes, in particular the air-sea interaction over the South China Sea during surges and the relationship of surges with convection, etc.

During Winter MONEX the surge were abnormally weak and the planetary scale

flow pattern was considerably different from some earlier years in both the tropics and midlatitudes. Comparisons between Winter MONEX and the winters of 1973-76 have already brought out important similarities and differences that help the understanding of cold surges. Systematic studies of the interannual variation for many years, and continuous monitoring of future years are required to advance our knowledge in the short-term climate variations of the winter monsoon and its possible interaction with other circulation systems such as circulations during other seasons and the Southern Oscillation.

3. LARGE-SCALE MOTION (FORCING)

3.1 Review of scientific objectives

The plans for the Winter Monsoon Experiment called for the investigation of a number of macro-scale features of the monsoon regime. These are listed below:

I. a. The mean and transient state of the Hadley-type monsoon circulation in the meridional plane.

b. The mean and transient state of the East-West (or Walker) circulation in the equatorial zonal plane.

c. The morphology of the Equatorial Trough in the Winter Monsoon region.

II. a. The identification and description of the heat-sources and sinks which drive the winter monsoon circulation.

b. The influence of orography on the winter monsoon circulation.

III. The interaction of the monsoon circulation with other circulation features. In particular:

a. Interhemispheric interactions.

b. The influence of middle latitudes on the monsoon regime.

c. The influence of the monsoon on the extratropics.

d. The interaction between the tropospheric equatorial circulation and the stratosphere.

The following paragraphs refer specifically to the progress by the scientific community towards achieving these scientific objectives.

3.2 The large-scale heating distribution and the atmospheric response

The distribution of the large-scale heating field is extremely complicated. Variability is obvious on synoptic time scales (Webster and Stephens, 1980) and on bi-weekly time scales (Sikka and Gadgil, 1980; Gadgil, 1982; McBride, 1982) and

is also apparent in the monthly mean distribution (Paegle and Baker, 1982). If we assume that infra-red irradiance may be used to indicate deep convection and the precipitating canopy clouds then satellite data obtained during Winter MONEX indicate significant variation. Compared to the long term mean seasonal heating which is centered over Indonesia (as indicated by Stephens et al., 1981), December 1978 showed a maximum in deep convection over the Java Sea, New Guinea and the equatorial South Pacific to the east of the Solomon Islands, whereas during January 1979, the convective activity appeared to shift southward with only moderate convective activity occuring over the Indonesian Islands. Although considerably more short lived the heating pattern appeared to resemble circulation features associated with the warm episodes (i.e., El Nino) in the East Pacific Ocean rather than the mean winter seasonal distribution (see Stephens et al., 1981; Lebmann and Hartmann, 1982).

In a series of studies (Johnson et al., 1981; Wei et al., 1981; Johnson and Townsend, 1981; Wei and Johnson, 1981) the large scale diabatic heating distributions were calculated for the FGGE year utilizing the isentropic mass continuity equation. Their results quantify the inferences obtained from the satellite irradiances by ascribing magnitudes to the region of maximum heating. For example, the maximum vertically averaged heating rates exceeded 1.5 K day^{-1} to the east of New Guinea*.

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*Some discussion ensued regarding the nature of the IIIb data set(s). Due to the current method(s) used in determining tropical motion the absolute magnitudes of the heating functions should be treated as tentative. In particular, normal mode initialization schemes tend to deemphasize divergent motion which constitutes a major component of the tropical flow.

Paegle and Baker (1982a) and Paegle and Baker (1982b) using the FGGE IIb data set of NASA-GLAS show similar characteristics to the isentropic analyses discussed above. Paegle and Baker (1982b) calculate global scale weekly and monthly energetics and momentum budgets which have particular relevance is interhemispheric interaction, to be discussed later.

Perhaps the strongest message emerging from the papers listed in the last paragraphs regards the scale and the importance of the Asiatic monsoon system. For example, Johnson and Townsend (1980) point out that throughout the year the Asian monsoon is a continuous heat source from which emanates a planetary scale regime dominating most of the eastern hemisphere. The isentropic analyses also allowed the relationships between the planetary scale transport of mass and energy to be established with vertical mass transports upward through isentropic surfaces in heat source regions and downward through the sink regions. The horizontal mass transport is from heat source to heat sink in higher valued isentropic layers and vice versa in lower-valued isentropic layers.

Considerable work using more conventional coordinate schemes has been undertaken using both the ECMWF and the NASA-GLAS level IIIb data sets (e.g., Paegle and Baker, 1982a, b). The results indicate very strong divergent inflow at 850 mb and outflow at 200 mb over the Indonesian, Borneo and equatorial Pacific Ocean and show a clear distinction between the northern hemispheric primary winter monsoon and the secondary southern hemisphere divergent circulation. Observed variabilities of the circulation appear to possess time scales of 2-4 weeks and even greater (Krishnamurti and Subrahmanyam, 1982).

There was a general consensus gained from a number of studies that prominent heating variations occur on all resolvable time and space scales. Kung and Paegle discussed the importance to the large scale aggregated heating of the diurnal cycle.

However, there was general consensus that while the magnitude was large and the variability a fundamental process of the convective tropics that its principal role was yet to be determined. It was suggested that the Bintolu radar data and the estimates of precipitation* be used to estimate the aggregated heating effect. Estimates of meso-scale heating and cooling were of order 20°C-30°C/day with the reduction to the global scale 1-3°C/day being attributed to compensations between the various components of the total diabatic heating function.

M. Murakami reported on recent results in which he extended the analysis of the time variability of the monsoon flow by a detailed study of the GMS data. Utilizing the original high frequency (8 times per day) IR data processed for every 1° grid, Murakami extracted an intensity index for convective clouds. First showing the mean monthly distribution of the intensity index matched the large scale deep convective activity pattern (the analysis matched distributions of Wei et al., 1981), M. Murakami then spectrally analyzed the data and exposed three principal periodicities; the diurnal cycle, a 5-6 day variability and a 10-15 day period. The diurnal variability possessed a maximum amplitude over Indonesia. The 5-6 day and the 10-15 day periodicities indicated that the winter monsoon was characterized by similar time scales as the summer monsoon (e.g., see Murakami, 1977; Krishnamurti and Bhalme, 1976; Sikka and Gadgil, 1980 for observations or Webster and Chou, 1980a, b and Webster, 1982 for modelling and theory).

A major research gap which became apparent during discussion is the evaluation of the sensible and latent heat fluxes at the earth's surface; both land and ocean. These fluxes are probably important over the entire winter MONEX region where cold northerly surges are predominant.

One of the most interesting results which is emerging from a number of studies

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*See section 5 on Clouds and Precipitation

is the interaction of the monsoon circulation on other regions and the interhemispheric interdependence of a number of phenomena. The scale of the monsoon and its planetary influence are discussed above. The interhemispheric aspects are discussed in section 3.4.

3.3 The influence of orography

One of the most elusive problems in the study of the general circulation has been the determination of the relative roles of orographic forcing and equatorial heating in producing the winter time circulation. On one hand, simple shallow water equation models show that the 300 mb flow perturbed by orography produces finite jet streams in the winter hemisphere which are very similar to observation. On the other hand, the low latitude heating maxima (e.g., over Indonesia in winter) are so located that they also could be responsible for the location of the quasi-stationary middle latitude flow.

In the winter monsoon regime the problem is even more complicated by the orographic structure of Indonesia and the effect it has on the overall large scale heating of the monsoon and the influence on various scales of motion. In Indonesia the effect of the mountains on local weather is extremely evident in the weather records (Ramage, 1971). However, the influence of tropical orography on the <u>larger</u> scale is still not understood and remains a critical problem for monsoon modelling and regional numerical weather prediction.

A number of studies have considered the effects of the higher latitude Tibetan Plateau on the monsoon flow. In particular, Murakami (1981) showed that during the 1978-79 winter low level winds tend to flow around rather than over the Plateau although a substantial part of the total flow still crosses over the mountain range. Murakami noted that the flow crossing the range results in pronounced descending

motion over northern China which enhances the subsident branch of the local Hadley circulation.

Murakami's study underlines the importance of the mechanical aspect of the Himalayas. He notes, however, that further study is needed to investigate the thermal effect of the mountains.

Model experiments by Nakamura and Murakami (1982) produced pronounced low-level cold surges and subsequent lee cyclogenesis on the east and south-east sides of a hypothetical facsimile of the Himalayas. The low-level cold surges were placed between small-scale low-level anticyclone and cyclone pairs which were induced by the topography. Starting on the northwestern end and propagating clockwise to the southeastern end of the mountain ellipse, the modes appear to be edge waves excited by the barrier. Similar features were noted by T. Murakami (1981) in the analysis of the 1978-79 winter data. It is believed that they are the first examples of Himalayan edge waves or Kelvin waves, to be identified although they appear to have some of the properties of edge waves observed on the southeastern coast of Australia.

The Himalayan edge waves and the subsequent lee cyclogenesis would appear to be quite important for day-to-day numerical forecasts. It would seem to be important to ensure that operational numerical models include sufficient orographic structure in order to simulate their evolution.

Paegle discussed other effects that orographic structures may have on the large scale flow. In particular, it was pointed out that topographic barriers appear to induce frequency shifts in mid-latitude synoptic scales. The relative energy in higher frequencies (i.e., synoptic time scales) increases from the west side to the east side of large mountain ranges. Similar analyses should be carried out for the MONEX region.

3.4 Large-scale interaction and the winter monsoon

In section 2, the interaction of mid-latitude events on the structure of the winter monsoon was the major subject of discussion. Except to say that the monsoon regions, both in winter and in summer provide a clear path for the influence of the extratropics on the tropics, we refer the reader to section 2.

In section 3.1, the role of the low latitude heating on the higher latitudes was shown to be quite large by a number of studies. The influence on higher latitudes has been more formally discussed in a number of recent theoretical papers (Webster 1981, 1982; Hoskins and Karoly, 1981) which stress the importance of low latitude heating on the winter hemisphere circulation. Although the three papers refer specifically to sea-surface temperature influence, they infer more generally that low latitude heating is an extremely important influence on the higher latitude circulation as long as the middle latitude winter westerlies encroach sufficiently equatorward to be excited. Another theoretical study (Webster and Holton, 1982) has shown that interhemispheric interaction may occur even if the zonally averaged flow is easterly, as long as a region of local westerlies exists somewhere along the equator.

A number of observational studies (e.g., Paegle and Lewis, 1982; Paegle and Baker, 1982a, b) has offered independent observational evidence for the theoretical suggestions discussed above. Paegle and Baker (1982a) show that during SOP 1 there are occasions when strong interhemispheric interactions of global scale fields take place. Mainly during episodes of zonally averaged equatorial westerlies. The basic mean zonally averaged flow is variable in time and may even change sign on a time scale of days. The asymmetric component is also strongly variable in time. A major problem is to understand why the zonal flow is so variable in time and, in particular, why the symmetric part changes sign. Paegle and Baker

(1982b) suggest that the sign change may only result from momentum exchanges with higher latitudes.

In summary, it appears that there is ample evidence from both observation and theory that the tropics and extratropics cannot be thought of as isolated regions. Nor can it be thought that one is alone in exerting its influence on the other. Rather the system appears to be cyclic with the low latitudes changing its character relative to influence from higher latitudes which due to these changes, influences the higher latitudes in turn.

Kung showed that there exists considerable connection between the middle latitudes and very high latitudes. He showed that in the sub-polar and polar region, the single major source of kinetic energy is the flux convergence of potential energy from the middle latitudes and that the circumpolar circulation is driven by the energy source from the middle latitudes. Changes in this driving appear to be associated with the cold surge phenomena.

3.5 Future research

A number of subjects which require considerable research has been highlighted in the previous pages. In particular, the role of the low latitude orographic structure as mechanical or heating agents is not understood at all. A program involving joint diagnostic and modelling efforts is necessary.

Perhaps the most important problem is the length of the data set. The three month period of the FGGE SOP 1 within which Winter MONEX resides can only allow inferences to be gained at the generality of the longer scale variability of the circulation. Thus it is important that these suggestions be compared with data sets of other years, although it is appreciated that these sets may not compare in quality with that obtained in SOP 1. What may help is the emerging Monsoon Climate Programme of the World Climate Research Programme which will produce a global scale, and ten year period data set.

4. REGIONAL SCALE RESEARCH

4.1 Review of scientific objectives

The primary scientific objectives of Winter MONEX include an important emphasis on regional scale aspects of the winter monsoon circulation. Specific objectives pertaining to this scale (and possibly to others) are:

I. <u>Heat sources</u>

a. the energy balance at the land and sea surface within the experiment area, including latent and sensible heat fluxes and the net radiational balance

b. the spatial and temporal distribution of condensational heating, as well as the determination of the fluxes of heat, moisture, mass and momentum within the atmosphere on the experiment area.

II. <u>Synoptic scale regional circulations</u>

To determine the thermodynamical and dynamical mechanisms responsible for the formation, maintenance and variability of synoptic-scale systems employing observations of the structure and life cycles of

a. cold surges

b. near equatorial disturbances

c. eastward moving upper tropospheric trough

III. <u>Improved prediction</u>

To develop improved techniques to forecast

a. impending cold surges and associated disturbances

b. floods and droughts as well as normal rainy and dry spells

4.2 Cold surges in the Winter MONEX region

In addition to the important planetary-scale circulation changes associated with cold surges, there are significant impacts on the local or regional scale

climate and weather of the winter monsoon region. In this section we will discuss these regional impacts, primarily focusing on the following aspects of cold surges: wind and thermodynamic structure, propagation characteristics, interaction with near-equatorial disturbances, initiation and modulation of heavy rainfall events in Indonesia and Malaysia and regional source characteristics.

A prominent regional feature of the cold surges is the sudden acceleration of northerly winds over the South China Sea in response to strong surface pressure rises over China north of Hong Kong. Ramage (1971) has noted that the acceleration of the winds over the entire span of the South China Sea is nearly simultaneous, as is the apparent intensification of East Asia local Hadley circulation (Chang and Lau, 1980, 1982; Lau et al., 1982; Johnson, 1982). Special Winter MONEX Soviet ship sounding data near 5°N just to the north of Borneo have clearly documented the accelerations in the north-south component of the wind in the lower and upper troposphere accompanying the surge events during December 1978 (Johnson and Priegnitz, 1981; Johnson, 1982). The low-level wind surges frequently extend across the equator into the region north of Australia and contribute to important enhancement of convection there (Williams, 1981; Love, 1982; Wirjohamidjojo, 1982) and, in addition, have a possible impact on tropical cyclone genesis in the southern hemisphere (Love, 1982). Several special Winter MONEX surface stations in the Java Sea were planned to monitor the southernmost extent of the cold surges, but implementation of the stations was not successful.

There were during the field phase, however, several data sources that permitted some investigation of the cold surge structure over the South China Sea. Aircraft dropwindsonde and flight level data form the NOAA P-3, NCAR Electra and Hong Kong Islander have been used to document the vertical structure of the lower troposphere for the moderate cold surge event of 10, 11 and 12 December (Simpson et al., 1981; Warner, 1982; Tsui, 1982). Warner (1982) has constructed vertical sections showing

the dramatic transition of the atmospheric structure along the trajectory of the cold surge from the suppressed shallow cumulus near Hong Kong to deep convection to the north of Borneo. The equatorward propagation of the leading edge of cold surges has been studied by Chang et al. (1983). Their analysis of surface data over the South China Sea has revealed that the pressure jump associated with cold surges propagates equatorward at $\sim 40\ m\ s^{-1}$, suggesting the cold surge can probably best be described as an internal gravity wave phenomenon.

Numerous studies have shown that cold surges frequently contribute to heavy rainfall along the east coast of West Malaysia, the north coast of Borneo and at many other locations in the Indonesian region (Ramage, 1971; Cheang, 1977). Although the cold surges during the Winter MONEX period did not exceed moderate intensity, there was the expected enhancement of tropical convection during the surge episodes in December 1978 (Houze et al., 1981b; Johnson and Priegnitz, 1981). Houze et al. found a greater modulation of equatorial convection and rainfall by the cold surges over water areas than over the land; however, only the region along the north coast of Borneo was investigated in any quantitative way in this regard. Further study is necessary to determine more complete regional distributions of rainfall enhancement (and in some places diminution) by cold surge events. As noted by Houze et al. (1981) and Johnson and Priegnitz (1981), the modulation of rainfall by cold surges is superimposed on a pronounced diurnal oscillation: this topic will be addressed in the next section.

The influence of cold surges on the intensity of cyclonic vortex disturbances near Borneo has been studied by Chang et al. (1979, 1982). Fluctuations in the strength of the Borneo vortex in association with cold surge events during winter MONEX were documented by Chang et al. (1982) using composited wind, temperature, surface dew point temperature and satellite data. They found that convective

cloudiness and 850 mb vorticity increase synchronously with the occurrence of cold surges in the South China Sea. The cold surge enhances and deepens the vortex, probably through increased organized deep cumulus convection.

In addition to interaction with the Borneo vortex, cold surges have been observed to interact with westward-propagating wave disturbances that enter the South China Sea from the western Pacific (Chang et al., 1979). At least one instance of such an interaction during Winter MONEX (on 16-17 December) has been noted (Johnson and Priegnitz, 1981).

Regional scale disturbances in cold surge source regions have recently been identified in numerical modeling studies (Nakamura and Murakami, 1982). Additionally, local secondary circulations over China associated with cold surge events have been documented (Boyle, 1982). The extensive and continuing dense data network over China offers the hope of additional detailed investigations such as these of regional characteristics of the cold surge at its source.

4.3 Near equatorial convective disturbances

In this section discussion will primarily center on the meso- to synoptic-scale convective systems which figure to be such a prominent feature of the equatorial convection over the Indonesian "maritime continent"; however, several other important topics will be mentioned first: the Borneo vortex, easterly waves, eastward moving upper tropospheric troughs and heavy rains in Malaysia and Indonesia which are orographically-induced or develop from smaller-scale convective systems. All of these phenomena need better description if there is to be hope for improved regional weather forecasting in the Winter MONEX region.

The dynamical structure and cloud patterns of quasi-stationary and westward propagating vortices near Borneo have been studied by Chang et al. (1982) by compo-

siting wind and satellite data. They found that the propagating type vortex disturbance is rather deep with a closed center identifiable and tilted southwest from gradient level through 500 mb, whereas the quasi-stationary vortex is shallow with its center defined only at 850 and 700 mb. The maximum cloudiness for the propagating type is in the northeast quadrant, but for the quasi-stationary type in the southwest quadrant.

There have been a limited number of investigations carried out on easterly waves in the winter monsoon region (Chang _et al_. 1979; Johnson and Priegnitz, 1981). Several researchers have followed the passage of easterly waves through the Winter MONEX region, especially the South China Sea area. One wave which passed the position of the Winter MONEX ship array near 110°E on December 5 eventually produced very heavy rain and flooding over the Malay Peninsula several days later (Johnson and Priegnitz, 1981).

Some work has focused on the interaction between easterly waves and the circulation of the Borneo vortices (Chang _et al_., 1979), but no general conclusions have been reached. The easterly waves appear to be best defined between 850 and 700 mb; consequently, there is some optimism that despite the poor data network to the east, they may be tracked with low-level satellite cloud wind data.

Frequently, heavy rains that occur along the coasts of Malaysia and elsewhere in the Winter MONEX region are a consequence of frictional convergence and orographic lifting of monsoon flow at the coastlines. While these regional rainfall events may be reasonably-well predicted, other smaller scale features are more difficult to forecast. As an example, a 24-hour record rainfall occurred on 2-3 December 1978 at Singapore (533 mm or 21 inches) not in association with a cold surge or any synoptic-scale equatorial disturbance, but rather as a result of the slow movement of a relatively small-scale convective cell or group of cells. The rela-

tive contributions to total rainfall from convection forced by monsoon surges, equatorial disturbances, land-sea breeze circulations and other processes, local or large-scale, are not well known.

The eastward movement through the Winter MONEX region of upper level troughs that extend to near the equator have been found by local forecasters in monsoon countries to have a significant effect on regional weather. The troughs, found at 300 mb, but often detectable to 500 mb, appear to modulate convective activity over Malaysia and other areas, resulting in distinctive wet and dry spells. In the northern part of the region these troughs can be tracked with conventional data across Asia to the Tibetan Plateau where they often split into northern and southern sections. An eastward moving trough resulting in westerly flow over Malaysia with its attendant dry weather did not occur during the December field phase. These troughs are poorly understood, but for local forecasters their importance to precipitation prediction is well established and further study of these systems is needed.

Probably the most extensively studied type of near equatorial convective disturbance during Winter MONEX is the mesoscale convective cloud cluster. On nearly every day during December 1978 a mesoscale cloud system developed during the early morning hours just to the north of Borneo (Webster and Stephens, 1980; Houze et al., 1981b; Johnson and Priegnitz, 1981; Johnson, 1982; Churchill, 1982; Johnson and Kriete, 1982; Warner, 1982). From composite and case studies of mesoscale cloud clusters in this region much has been learned regarding their structure and characteristics as well as their modulation by cold surges. A prominent feature of these cloud clusters is the development during the mature stage of a mesoscale ($\sim$100 - 300 km) anvil or stratiform-type cloud shield characterized by light continuous precipitation (Houze et al., 1981b; Churchill, 1982). These cloud systems

potentially have an important impact on the net radiative heating field over extensive areas (Webster and Stephens, 1980). Mechanisms which possibly contribute to the growth and maintenance of these cloud systems have been studied by Webster and Stephens (1980), Houze (1982) and Johnson and Kriete (1982). Details of findings on mesoscale cloud cluster structure, initiation machanisms and large-scale heating effects are presented in Section 5. It is important to note that these convective systems have significant outflow extending to the synoptic ($\sim$1000 km) scale in the upper troposphere (Johnson and Priegnitz, 1981).

Recent work has also shown that the winter monsoon mesoscale convective systems have an important effect on the large-scale temperature field in the lower stratosphere. Sounding data from Soviet ships over the South China Sea north of Borneo have been uniquely valuable in determining the existence of significant cold anomalies ($\sim$6°C) atop the mesoscale anvil clouds near the tropopause and extending several km into the lower stratosphere (Johnson and Kriete, 1982). Whether these cold anomalies are caused by radiative effects, cumulonimbus overshooting, mesoscale ascent or a combination of these effects is not known and further study is needed.

The diurnal controls on convection by land-sea breeze circulations in this part of the world are remarkable, as has long been known (e.g., Ramage, 1971; Riehl, 1979). The recent availability of geostationary satellite data has permitted quantitative analysis of characteristics of the diurnal convective pattern over the entire Malaysia-Indonesia region (M. Murakami, 1982). The diurnal cycle of maximum convection over land at 1800 L and over water at 0900 L found by M. Murakami raises questions about possible diurnal variations in net condensation and its vertical distribution, variations that may create diurnal modulations of the Hadley-Walker circulations of the monsoon system.

4.4 Regional numerical prediction

Numerical weather prediction relevant to winter monsoon objectives has been addressed with a global model at Florida State University (Krishnamurti, 1982, personal communication). The studies address the results of a number of experiments with the FGGE IIIb plus data sets from MONEX platforms as well as the high resolution cloud winds. The model is global spectral and uses 29 waves. The initial state for all experiments is 00 GMT, 10 December 1978.

Results of the experiments relevant to regional problems are:

1) A five level vertical resolution fails to describe the cold surges from the Asian continent into the South China Sea even for periods as long as 2 days. The Pacific Northeast trades penetrate the South China Sea and enter the Bay of Bengal. The 11 level model provides a better boundary layer description of the cold surges, which are handled very well to 6 days.

2) The 11 level model describes the formation of a surge vortex in the South China Sea relatively well by day 4 and the vortex is carried along slowly westward by day 6.

3) The inclusion of high resolution cloud winds show very little improvement over the ECMWF analyses which do not contain this data set.

4) The predicted patterns of large scale 24 hour rainfall totals show a sequence of changes near Borneo that resemble the observed changes of rainfall rates noted from the Soviet ship observations. The model was noted to predict rainfall intensities of the order of 25 mm day^{-1} over this region.

5) The intensity of the cold surge especially on 11 December was predicted very well by the model with the higher resolution.

6) Further experiments on the sensitivity of monsoon to heating fields, diurnal cycles and different data sets need to be carried out.

4.5 Future research

Because of the limited scope of the field experiment and nature's lack of cooperation (no strong surges during December 1978), documentation of surge characteristics from Winter MONEX data is rather limited. The vertical structure of only one moderate cold surge has been reported (Simpson et al., 1981; Warner, 1981, 1982). Strong surge characteristics are not well known. Probably some additional analysis of cloud and boundary layer structure are possible with existing Winter MONEX data (e.g., using aircraft boundary layer data from a single low level flight over the South China Sea).

The vertical structure of the cold surge as it crosses the equator is not well known and further analysis with Winter MONEX data, particularly the Soviet ship data for January 1979, is possible.

Future experiments involving cold surges should stress more detailed analysis of their horizontal (cross-hemisphere) and vertical structure. The temporal variation also is worthy of continued study.

With regard to propagation characteristics of cold surges, the lack of surface pressure analysis of the surge events into the Southern Hemisphere is particularly noteworthy. Satellite data suggest propagation across the Java Sea, but analysis of this propagation is limited (Williams, 1981; Wirjohamidjojo, 1982). Special networks of surface stations reporting pressure, temperature, dew point and wind over the entire winter monsoon region both north and south of the equator are needed in future studies of monsoon surges.

The interaction of cold surges with equatorial disturbances is difficult to study with the existing Winter MONEX data because of (1) the lack of a strong event during the field phase period and (2) inadequate resolution of Winter MONEX special platform data. Future experiments should be fully aware of the above limitations and also focus some attention to the nature of westward propagating wave disturbances

and their interaction with cold surges.

Other than in the north Borneo region, no significant analyses of regional heavy rain systems have been carried out using Winter MONEX data. Clearly and most importantly from the standpoint of local weather prediction, future experiments must necessarily focus resources on regional heavy rain events.

The modulation of equatorial convection by surges is still not fully understood. Observational studies of convective activity over many regions of Indonesia and surrounding area (e.g., Java Sea) are still lacking. Some works have indicated that eastward and westward propagating cloud clusters can be identified in the equatorial region after northeasterly cold surges. This kind of cloud formation could be an important part of the convective modulation over the tropical Pacific. More observational analyses should be encouraged over regions other than the South China Sea.

An important aspect of the regional equatorial convective response to cold surges needs further study, namely, land vs. ocean differences in convective structure and vertical heating distributions. For example, if the vertical distribution of condensational heating over ocean is different from that over land, then the land-sea breeze circulations of the region, which generate a predominance of convection over water at night and land at day, should produce important diurnal variations in the tropical convective heating response to cold surge activity.

Although several atlases (Sadler, 1979; Chang et al., 1981) and gridded data sets (Simpson et al., 1981; Murakami et al., 1981) have appeared, the coarseness of the actual data presents a real problem. Chu (1982) is preparing a gridded data set covering the domain 10°S - 35°N and 90°E - 130°E with 2.5° latitude spacing, twice per day during 8-30 December and at 10 mandatory levels from 1000 to 150 mb. The data set will be used for a variety of purposes which include (1) a description of the December mean fields of wind, temperature and mixing ratios, (2) diagnostic

and phenomenological studies of the relationships between the Borneo cyclone, surface pressure trough and cold surges, and (3) budget studies (mass and energy) on synoptic scales during the surge and non-surge periods. An extension of this work to December 1980 is contemplated using the conventional upper air and GMS-1 data with the objective of comparing seasons having strong and weak surge activity.

In addition, work is underway at the University of Wisconsin to evaluate the performance of two techniques to estimate rainfall using satellite data. The techniques are "life-history" method (Stout et al., 1979) and "grid-indexing" method (Martin and Howland, 1982). One of the techniques will be used to produce a set of three hourly rainfall maps for the period 8-30 December 1978. These data will be useful for the studies of large-scale budget of heat and moisture.

Future experiments must carefully consider data density needs relative to the scale of the regional disturbances under study. Only a few regional scale systems during Winter MONEX can be investigated in detail since data resolution for this purpose is limited. Research aircraft flights into strong disturbances will be necessary. Preferred regions for heavy rainfall should be determined and several focused studies on such regions be undertaken.

The eastward moving upper tropospheric troughs have received little attention in the literature. Because they are of synoptic-scale, the conventional or a slightly-enhanced conventional sounding network will probably shed light on the salient dynamics features. Diagnostic or modeling studies on the large scale should be capable of clarifying the role the troughs play in wet and dry spells, although eventually regional models may be necessary.

As of this time only Krishnamurti has carried out numerical prediction studies that have weather prediction implications in the near equatorial regions. The work of Nakamura and Murakami (1982) may have some impact on prediction downstream of the Tibetan Plateau.

Additional modeling efforts on the regional scale need to be carried out. One potential candidate for numerical modeling on the sub-synoptic scale is the diurnal mesoscale convective system that regularly occurs to the north of Borneo (Houze _et al_., 1981b; Johnson and Priegnitz, 1981). Models of other regional convective and non-convective phenomena can be developed, but it must be recognized that on the sub-synoptic scales Winter MONEX data are quite limited. Future experiments should, in particular, address the needs of limited domain or nested regional models.

5. CLOUDS AND PRECIPITATION AND RELATIONSHIP TO LARGE AND REGIONAL SCALE MOTIONS

One of the major goals of WMONEX was a better description and understanding of winter monsoon clouds and precipitation, both in terms of their structure and their relationship to large-scale and local flow patterns. Over 50 cm of rain falls along the north coast of Borneo in December, and Ramage (1971) has pointed out that the latent heat released in the clouds and precipitation that forms in this region in winter constitutes the single greatest source of energy for the atmosphere. This heating drives the large-scale monsoonal circulation (Webster, 1972), and the vertical redistribution of energy accomplished by the clouds provides vertical coupling between the lower and upper troposphere where the heat is released (Manabe et al., 1970).

Cloud and precipitation studies are also central to the problems of regional forecasting in the winter monsoon region. Heavy rains and flooding occur in sub-synoptic scale episodes associated particularly with cloud clusters embedded within the larger-scale flow. The predictability of these events requires knowledge on scales ranging from cumulus to planetary.

Prior to WMONEX, the structure of clouds in monsoon regions had been described only in the broadest terms; for example, "showers" from towering cumulus and cumulonimbus (Ramage, 1971). To understand the link between planetary-scale monsoonal overturning and cloud-scale heating, and to improve local forecasting of monsoon rains, it was necessary to carry out basic studies to obtain more specific information on the nature of winter monsoon clouds than had been available previously. The studies that have been conducted have employed WMONEX aircraft, radar and satellite observations to document:

1) The characteristics of winter monsoon cloud populations, particularly over the southern part of the South China Sea

2) The structures of the major cloud clusters from which most of the winter monsoon precipitation falls

3) The effects of the cloud air motions and structures on the vertical distribution of heating that occurs in the WMONEX region

4) The relationship of the occurrence of winter monsoon cloud systems to synoptic-scale and diurnal forcing.

5.1 Cloud population and characteristics

Studies of cloud population characteristics have been carried out by Webster and Stephens (1980), Warner (1981, 1982) and Churchill and Houze (1983). Over the South China Sea in December, the distribution of clouds ranging from small cumulus to large cloud clusters is basically similar to the distribution of clouds found over other equatorial oceans. The smaller clouds dominate numerically, are deformed by wind shear, and are organized into mesoscale groups, including arc lines, with intervening mesoscale clear areas. The clouds appear to have the rather weak updraft and downdraft intensities similar to those found in GATE and in hurricanes. The larger cumulonimbus is organized into mesoscale convective systems referred to as cloud clusters. The clusters are characterized by widespread mid-upper level cloud shields, the cirriform tops of which dominate satellite imagery of the region. These clusters account for practically all of the winter monsoon precipitation.

5.2 Cloud cluster structure

The structure of the cloud clusters over the South China Sea have been studied by Houze et al. (1981a, b), Johnson and Priegnitz (1981), Johnson (1982), Johnson

and Kriete (1982), Warner (1982), Churchill (1982) and Churchill and Houze (1983). These studies show that these clusters have life cycles and structures generally similar to cloud clusters observed in other parts of the tropics, especially those observed in GATE. These clusters conform to the life cycle described by Leary and Houze (1979), Houze and Betts (1981), Houze (1982) and Houze and Hobbs (1982). In its early stages, a cluster consists of a group of deep convective cells. The cells then merge to form a mesoscale system. As the number of cells increases, the cluster forms a mid-upper level cloud shield, which is quite stratiform. Non-convective rain falls from the cloud shield, so that the mature system consists of a combination of convective cells and stratiform clouds and precipitation. As the system ages, it becomes increasingly stratiform. In its final stages, its only remnant is a broad sheet of cirrus cloud. Over the lifetime of a well formed cluster, about half the rainfall is stratiform.

In addition to confirming that the clusters were generally similar in their structure and development to GATE cloud clusters, the WMONEX data provided new information on cloud cluster structure. Winter MONEX aircraft and radar observations provided unprecedented data on the microphysical structure at upper levels in both the convective cells and the stratiform cloud shield. The convective cells are characterized by rimed particles, while the stratiform cloud shield exhibits vapor grown crystals. Vertical profiles of radar reflectivity together with the aircraft microphysical data allow the ice budget of the stratiform cloud shield to be determined and indicate that a mesoscale updraft was present in the cloud shield (Churchill, 1982). The magnitude of the mesoscale upward motion determined from the microphysical analysis agrees with vertical motions deduced from the WMONEX ship soundings (Johnson, 1982). The ship data and aircraft dropwindsondes further show that mesoscale downdraft occurred below the base of the stratiform cloud shield.

The work of Johnson and Kriete (1982) reveals that significant mesoscale cooling occurs at and above the tops of the stratiform cloud shields of WMONEX cloud clusters.

The structural studies of WMONEX cloud clusters show clearly that winter monsoon convection is dominated by cloud clusters whose air motions and precipitation processes are organized on the mesoscale. Simple models of a group of convective cells do not apply to winter monsoon convection.

5.3 Cloud cluster heating effects

The mesoscale structure of winter monsoon cloud clusters gives rise to heating effects that would not be present without the mesoscale organization. Work on the vertical profiles of heating has been carried out by Webster and Stephens (1980) and Houze (1982). The former authors show that combined long- and short-wave radiation provides net heating and increases the lapse rate in mesoscale cloud shields such as those of winter monsoon cloud clusters. Houze (1982) showed that in addition to radiation, processes associated with the mesoscale stratiform precipitating cloud shield of a cluster warm the upper troposphere, as a result of condensation in the mesoscale updraft, and cool the lower troposphere as a result of melting and evaporation of the stratiform rain in the mesoscale downdraft. When added to the heating by the deep convective cells in the cluster, the heating and cooling associated with the mesoscale stratiform features of the cloud cluster substantially change the vertical profile of net heating associated with the cluster. These effects should be accounted for in assessing the effect of winter monsoon convection on larger-scales of motion.

As an illustration of the implications of the effects of the mature cluster heating profile on larger-scale motions, Hartmann _et al_. (1983) have recently ob-

tained the linear steady-state response to heating for the distinctly different heating profiles of average tropical conditions and of a mature cluster such as that described by Houze (1982). They suggest that the mature cluster heating profile may be the more appropriate one for studies involving large-scale perturbations in tropical heating. Their view is supported by calculations which show that the mature-cluster heating profile produces a more realistic Walker Circulation than a more conventional profile. They also show that when the two heating profiles are placed at 14°N they produce rather different mid-latitude responses for average winter conditions.

The work referred to above refers to vertical profiles of heating. The total amount of heating to be distributed in the vertical is indicated by patterns of cloudiness and precipitation in the maritime continent region. Current work reported at the Workshop by M. Murakami (satellite) and S. Geotis (radar) will aid in determining the actual amounts and patterns of heating that occurred in Winter MONEX.

5.4 Synoptic and mesocale forcing of cloud formation

It is generally recognized that cloud clusters occur in response to static instability and low-level convergence. The low-level convergent regions of synoptic scale disturbances provide favorable forcing, but still more focussed convergence on the mesoscale is usually required to release instability sufficiently for a cluster to form. The maritime continent is a prolific generator of clusters. The islands and peninsulas set up land-sea circulations, which produce mesoscale convergence offshore at night and over land by day. The work of Houze et al. (1981b), Johnson and Priegnitz (1981), and Johnson (1982) documents the land-sea circulation and presents a detailed analysis of the triggering of convection at night off the

the north Borneo coast. The diurnally generated offshore lower-tropospheric wind converges at night over the sea with the northeasterly monsoon surface winds and thus triggers a cluster over the water. When the synoptic conditions become more favorable for convection during surges, the general level of cloud cluster activity increases, but the diurnal modulation remains, and even appears to be stronger, during these periods.

5.5 Future experiments

At the Workshop, presentations were made proposing a future field experiment in the maritime continent area -- probably staged out of Darwin, Australia. As proposed the experiment would concentrate on multi-level aircraft and remote sensing of cloud clusters. Such an experiment would provide the logical next generation of data. The experiment would concentrate on cloud systems, which were investigated secondarily to large-scale flow patterns in Winter MONEX. The proposed sampling would therefore provide more detailed measurements from which the vertical distribution of heating, which has been inferred rather indirectly from the present generation of data, could be documented in more detail. The vertical heating profile appears to be a crucial aspect of the monsoon problem, and its character is determined on the mesoscale. The mesoscale emphasis of the proposed experiment is necessary to make progress on this problem.

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APPENDIX A

WINTER MONEX WORKSHOP AGENDA

Room 260 Ingersoll Hall, Naval Postgraduate School

Monday June 14, 1982

9:00 am - 9:10 am	Opening remarks	C.-P. Chang/ J. A. Young
9:10 am - 10:25 am	Large Scale I	
	Overview	P. J. Webster
	Planetary-scale teleconnections during surges	K. M. Lau
	Cross-hemispheric surges of mass and energy	W. M. Gray
	Theory of surge-forced tropical motions	H. Lim
	Surface structure of surges over Winter MONEX area	C.-P. Chang
10:25 am - 10:45 am	Break	
10:45 am - 12:00 pm	Small Scale I	
	Overview	R. A. Houze
	Meso-scale features of Winter MONEX convection	C. Warner
	Aircraft and ground based radar measurements	D. D. Churchill
	Rainfall estimates from the Bintulu radar	S. G. Geotis
	Radiative destablization of extended clouds	G. L. Stephens
12:00 pm - 2:00 pm	Lunch	
2:00 pm - 3:30 pm	Large Scale II	
	Large scale effects of topography	T. Murakami
	Synoptic study of the initiation of surges	J. S. Boyle
	Diagnostic study of large-scale heating during Winter MONEX	M. Y. Wei
	Variation in the large scale heat sources during SOP-I	J. Paegle
	Temporal variation of satellite cloudness during Winter MONEX	M. Murakami
	Energetics of winter monsoon flow	E. C. Kung
3:30 pm - 3:50 pm	Break	
3:50 pm - 4:50 pm	Small Scale II	
	Synoptic and mesoscale structure of Winter MONEX convection	R. H. Johnson
	Structure of synoptic scale cyclonic circulation near Borneo	G. T. Chen
	South China Sea disturbances during Winter MONEX	D. N. Sikdar
	Satellite rainfall estimate and data analysis over South China Sea	J. H. Chu
4:50 pm - 5:15 pm	General discussion and organization of groups	

Tuesday June 15, 1982

8:30 am - 10:15 am	Discussion and report writing by small working groups Large Scale (Cold Surge) - Ingersoll 260 Large Scale (Forcing) - Ingersoll 260 Small Scale (Regional/Synoptic) - Ingersoll 285 Small Scale (Cloud and Precipitation) - Root 252A
10:15 am - 10:30 am	Coffee break - Ingersoll 260
10:30 am - 11:25 am	Report by small working groups and discussion - Ingersoll 260
11:25 am - 1:25 pm	Lunch
1:30 pm - 2:30 pm	Report by small working groups and discussion (continued)
2:30 pm - 3:30 pm	Modification by combined working groups Large Scale - Ingersoll 260 Small Scale - Ingersoll 285
3:30 pm - 3:45 pm	Break
3:45 pm - 5:15 pm	Discussion of future directions

Large Scale		Small Scale	
Cold Surge	Forcing	Regional/Synoptic	Cloud and Precipitation
J. S. Bolye	T. N. Krishnamurti	G. T. Chen	D. D. Churchill
C.-P. Chang*	E. C. Kung	J. H. Chu	S. G. Geotis
W. M. Gray	T. Murakami	R. H. Johnson*	R. A. Houze*
K. M. Lau	J. Paegle	M. Murakami	G. L. Stephens
H. Lim	P. J. Webster*	D. N. Sikdar	C. Warner
J. A. Young	M. Y. Wei	P. L. Stephens	F. D. White

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APPENDIX B

WINTER MONEX WORKSHOP

List of Participants

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