An Energetics Analysis of Cyclonic Development in the Asian Winter Monsoon¹

By Stephen E. Masters² and Ernest C. Kung

*Department of Atmospheric Science, University of Missouri-Columbia,
Columbia, Missouri 65211 U.S.A.*

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Abstract

Energy transformations of cyclonic development in the Asian winter monsoon from the Asian continent to the western Pacific are studied for the FGGE year. Computational analysis is done with a moving area defined for each observation encompassing the primary storm system. Energy budgets are grouped according to the evolving stages of the storm system to derive a composite view of storm development. Five individual cases are also selected and examined.

A very significant portion of kinetic energy generation, 86%, is from local baroclinic conversion by eddies. This consistent with the fact that the cyclone growth takes place over the ocean. However, there is an additional energy source within the storm system. The amount of eddy conversion also depends on the storm path, with the largest conversion in cases of rapidly developing storms over a large area of the warm ocean. The intensity and balance of kinetic energy change drastically from its incipient stage to the late mature and actively occluded stages. In the incipient stage generation and export of kinetic energy are the largest, while dissipation is the smallest. As generation and export decrease, dissipation increases sharply to the later stages of development. In these later stages, the system also imports a large amount of kinetic energy.

1. Introduction

The winter monsoon over eastern Asia and the western Pacific is well recognized as one of the most prominent features in the Northern Hemisphere. During the winter months, a high pressure dome of extremely cold air builds up over Siberia and parts of China. As the large-scale systems move eastward, cold air periodically breaks out over eastern China and the western Pacific, often penetrating deep into the tropics. Intense cyclones are observed to develop rapidly in the vicinity for the East China Sea and move northeastward into the Aleutian area where

they lose their identity. A very strong jet stream extends eastward from central China, across Japan into the western Pacific, and it is shown that very intense transformations take place in the maintenance of kinetic energy in this region (Kung, 1977b; Kung and Chan, 1981).

As the cold air moves over the warm water, an intense air mass modification takes place. In the Air Mass Transformation Experiment of February 1974 and 1975, heat transfers from the ocean to the atmosphere at rates of 500 to 800 W m⁻² were computed (Garraat and Hyson, 1975; Nitta, 1976). As discussed in Kung (1977b) and Kung and Siegel (1979), most of the heat energy added to the atmosphere from the ocean surface should be directly added to the reservoir of available potential energy of the general circulation,

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2 Current affiliation: ENSCO, Inc., Indian Harbour Beach, Florida 32937.

while a relatively small portion is utilized locally in the growth of cyclonic disturbances through baroclinic conversion. However, as verified by numerical experiments (e.g., Robertson and Smith, 1983), this local use of latent heat significantly influences the developing storm in its synoptic and energetics structure. Chen *et al.* (1985) show that release of latent heat from Kuroshio results in the development of the medium-scale cyclone, and the vertical coupling of the cyclone with the incoming upper-level synoptic system leads to the development of the severe extra-tropical storms.

Since the 1970's, the increasing number and quality of upper-air observations as well as development of appropriate analysis schemes have allowed an energetics diagnosis of the winter monsoon on a regional basis. Ninomiya (1976) studied the kinetic energy budget in the mixed layer over the Kuroshio. Kung (1977b) analyzed the large-scale energy transformation over the Kuroshio region. Kung and Chan (1981) described the energetics of the winter monsoon in Siberia, northeast Asia, China and the Japan Sea. Masters and Kung (1983) reported on an energetics budget of the Aleutian low area. Each of these regions is found to exhibit distinct energetics features reflecting their specific mechanism of energetics maintenance. The problem of the relationship between the large-scale energy field and mesoscale convection also receives attention (e.g., Sheu and Smith, 1977; Sheu and Agee, 1977).

The First GARP (Global Atmospheric Research Program) Global Experiment (FGGE) data sets provide grid data coverage over the normally data-sparse areas through four-dimensional assimilation of both standard and non-standard meteorological observations. In this study the FGGE Level IIIb data produced by the Geographical Fluid Dynamics Laboratory (see Miyakoda *et al.*, 1982; Ploshay *et al.*, 1983) are utilized to examine the energetics of cyclonic development in the winter monsoon system from the Asian continent to the western Pacific. Energy budgets are computed with a moving area encompassing the primary monsoon storm systems. They

are then grouped according to the evolving storm stages to derive a composite view of storm development. The five selected individual storm cases are also closely examined with respect to transformation processes.

2. Energy equations and scheme of analysis

In the framework of primitive equations in the hemispherical polar coordinates, the kinetic energy balance of the atmospheric flow in a pressure layer over an area may be written as

$$\left[\frac{\partial k}{\partial t} \right] = -[\nabla \cdot \mathbf{V}k] - \left[\frac{\partial \omega k}{\partial p} \right] - [\mathbf{V} \cdot \nabla \phi] - [E] \quad (1)$$

where $k = \frac{1}{2} \mathbf{V} \cdot \mathbf{V}$ is the kinetic energy per unit mass, $\mathbf{V}$ the horizontal wind vector, t the time, p the pressure, ϕ the geopotential, ∇ the horizontal del operator, $\omega = dp/dt$ the vertical p -velocity, and E the dissipation. The bracket $[\]$ on a dummy variable X per unit mass denotes an area mean over a limited mass of the atmosphere

$$[X] = \frac{1}{gA} \int_{p_1}^{p_2} \int_A X dA dp \quad (2)$$

where g is the acceleration of gravity, A is the area of the region, and $p_2 > p_1$. The variable X then may be expressed as

$$X = [X] + X' \quad (3)$$

where the eddy quantity X' is the departure of X from $[X]$.

In Eq. (1), $[\partial k / \partial t]$ is the local time change of kinetic energy, $-\nabla \cdot \mathbf{V}k$ the horizontal flux convergence or horizontal transport, $-\partial \omega k / \partial p$ the vertical flux convergence or vertical transport, and $-\mathbf{V} \cdot \nabla \phi$ the cross-isobaric generation. As the generation term $-\mathbf{V} \cdot \nabla \phi$ is the internal source or supply of kinetic energy from the reservoir of available potential energy, the transport terms $-\nabla \cdot \mathbf{V}k$ and $-\partial \omega k / \partial p$ are external sources of kinetic energy imported to the defined mass of the atmosphere over the region. Dissipation $[E]$ is the residual term to balance the kinetic energy equation (1). Although

Fig. 1 The $4^\circ \times 5^\circ$ data grid in the region of analysis.

$[E]$ is related to the eventual frictional dissipation, in the regional analysis the residual term $[E]$ may not be equated to true frictional dissipation. It may be recognized as the sink of kinetic energy from the observed scale.

The generation term may be expressed as the summation of the three process terms

$$-[V \cdot \nabla \phi] \\ = -[\nabla \cdot V \phi] - [\partial \omega \phi / \partial p] - [\omega \alpha] \quad (4)$$

where α is the specific volume of air. In Eq. (4), $-\omega \alpha$ is the conversion of available potential energy to kinetic energy, and $-\nabla \cdot V \phi$ and $-\partial \omega \phi / \partial p$ are horizontal and vertical transport of available potential energy. Eq. (4) may be further written as

$$-[V \cdot \nabla \phi] = -[\nabla \cdot V \phi] - [\partial \omega \phi / \partial p] \\ - [\omega][\alpha] - [\omega' \alpha'] \quad (5)$$

where $-\omega[\alpha]$ and $-\omega' \alpha'$ are regarded as baroclinic conversion by mean and eddy motion respectively.

The original GFDL FGGE Level IIIb data on a $1.875^\circ \times 1.875^\circ$ latitude-longitude grid were interpolated to a $4^\circ \times 5^\circ$ grid by Kung and Tanaka (1983). The $4^\circ \times 5^\circ$ grid points

in the region of this study are shown in Fig. 1. A total of 114 observation times constitute the data period from 0000 GMT 2 January to 1200 GMT 27 February 1979 in this analysis. The twice-daily grid values of the wind, temperature, geopotential height, and vertical p -velocity to 1000, 850, 700, 500, 400, 300, 350, 200, 150, and 100 mb are the basic input for the energetics computation. The evaluation of energy variables follows the computational scheme for regional energetics as described by Kung (1977b), Kung and Chan (1981), and Masters and Kung (1983). No explicit correction for topography is done, and the surface is represented by the 1000 mb level.

National Meteorological Center operational analyses of the surface, 500 mb and 300 mb levels were examined at 0000 and 1200 GMT during the data period over the winter monsoon region (see Fig. 1). The primary synoptic-scale cyclones in the region were identified for the individual observation times, and classified according to their developmental stage. The criteria to identify the stages of storm development are as follows:

Class stage	Description
1 Incipient stage	<p><i>Surface.</i> Development just beginning. Trough or forming cold front evident at the surface. Surface cyclone development impending within 12 hours.</p> <p><i>500 mb.</i> Strong short wave trough discernable west of the developing surface system.</p> <p><i>300 mb.</i> Weak short wave trough slightly west of the 500 mb trough position.</p>
2 Developing stage	<p><i>Surface.</i> Weak but developing surface low (one or two closed isobars, central mean sea level pressure around 1000 mb). Cold front formed at the surface; fronts in an open wave configuration. Cold anticyclone building eastward to the west of the storm.</p> <p><i>500 mb.</i> Trough west of the surface low center. Closed low may be seen in eastern Siberia north of the trough.</p> <p><i>300 mb.</i> Short wave is more distinct than in the incipient stage, located west of the surface low and 500 mb trough line.</p>
3 Early mature stage	<p><i>Surface.</i> Occluded front beginning to form. Mean sea level central pressure 985-1000 mb. Cold front pushing rapidly eastward with high pressure building from the west behind the front.</p> <p><i>500 mb.</i> Strong trough located just west of the surface center. Upper system has slowed its motion.</p> <p><i>300 mb.</i> Moderately deep trough located west of the surface center. Flow around trough is quite strong.</p>
4 Late mature stage	<p><i>Surface.</i> Strong, deep surface low with occlusion continuing. Surface pressure 970-990 mb. Cold front still pushing eastward, especially near the low center. Surface center motion slowing. Evidence of secondary storm development along the southern areas of the cold front may be seen.</p> <p><i>500 mb.</i> Closed cyclone over the surface center. Storm system is nearly stationary just east of the Asian coast.</p> <p><i>300 mb.</i> Trough over the surface and 500 mb centers.</p>
5 Active occluded stage	<p><i>Surface.</i> Very strong cyclone with central pressure less than 975 mb, and well occluded. Warm sector insignificant. Storm is nearly stationary in the vicinity of the Aleutian Islands. Cold outbreak has swept over most of the area of analysis as far south as 15°-20°N.</p> <p><i>500 mb.</i> Strong closed low over the surface center is the dominant feature of the northeastern portion of the region.</p> <p><i>300 mb.</i> Strong and possibly closed trough stationary over the surface and 500 mb centers.</p>

Idealized flow patterns at the surface and 500 mb for these five stages are illustrated in Fig. 2. The classical synoptic life cycle will carry a storm from stage 1 through stage 4, and the stronger, more active systems may

attain the stage 5 classification in their occluded stage. Many storms during the FGGE, however, developed slowly and weakly, reaching only a stage 2 or 3 classification. For the purpose of energetics analysis, the

Fig. 2 Synoptic classification model.

Fig. 2 (continued)

area of storm influence or synoptic low region is defined in terms of a spherical rectangle, bounded by parallels and meridians, that encloses the cyclonic surface flow and the cyclonic portion of the upper trough. At any one observation time, only one storm system with its associated synoptic low region is defined as the primary system. Once a storm forms and is defined as the primary system, its life cycle is followed until it decays or moves out of the analysis region east of 170°E .

The primary systems are thus identified in 87 observation times during the period. These systems are listed in Table 1 with the synoptic low region as defined by their respective boundaries. By defining such boundaries of analysis for individual observation times, energy variables may be evaluated over the

moving area of storm influence. For the other 27 observations during the period, no storm system is recognized in the area and so they are eliminated from further analysis.

3. Composite energetics of cyclonic development

The gross energy budget of all identified primary systems is shown in Table 2. The kinetic energy level $[k]$ with a vertical total of $33.26 \times 10^5 \text{ J m}^{-2}$ is significantly higher than $15 \times 10^5 \text{ J m}^{-2}$ in a long-term mean budget of cyclones in North America (Kung and Baker, 1975). It is comparable to, but smaller than, $45 \times 10^5 \text{ J m}^{-2}$ as given by Kung and Chan (1981) over China Main and the Japan Sea for the winter monsoon in association with the intense portions of the westerly jet. The kinetic energy balance of storm systems in

Table 1 Identification of primary systems and their boundaries of analysis for individual observation time.

Date (Time GMT)	Synoptic class	Boundaries of analysis				Surface storm		
		North	South	East	West	Center location	Central pressure	
3 Jan 79 (12)	2	63° N	33° N	142° E	94° E	56° N	142° E	1004 mb
4 Jan 79 (00)	3	68°	38°	150°	100°	58°	144°	994
4 Jan 79 (12)	3	63°	22°	152°	108°	56°	150°	992
5 Jan 79 (00)	3	64°	20°	154°	108°	60°	148°	996
8 Jan 79 (00)	2	60°	36°	155°	104°	50°	136°	1001
8 Jan 79 (12)	2	61°	35°	153°	110°	54°	143°	992
9 Jan 79 (00)	3	61°	33°	160°	125°	56°	147°	992
9 Jan 79 (12)	4	60°	35°	165°	125°	58°	148°	988
10 Jan 79 (00)	1	56°	34°	143°	108°	40°	134°	1013
10 Jan 79 (12)	3	63°	22°	159°	117°	46°	148°	992
11 Jan 79 (00)	4	60°	23°	167°	125°	47°	158°	968
11 Jan 79 (12)	5	63°	23°	170°	120°	53°	166°	960
12 Jan 79 (12)	2	41°	19°	150°	109°	30°	145°	1006
13 Jan 79 (00)	2	44°	22°	155°	117°	35°	147°	1003
13 Jan 79 (12)	2	53°	25°	170°	122°	35°	160°	984
15 Jan 79 (00)	1	48°	20°	149°	100°	—	—	—
15 Jan 79 (12)	2	50°	20°	155°	110°	36°	151°	1006
16 Jan 79 (00)	2	50°	20°	168°	120°	40°	167°	998
17 Jan 79 (12)	1	56°	30°	150°	100°	34°	125°	1012
18 Jan 79 (00)	3	50°	20°	151°	110°	40°	138°	1001
18 Jan 79 (12)	4	54°	20°	157°	105°	38°	147°	981
19 Jan 79 (00)	5	54°	20°	163°	115°	42°	158°	964
19 Jan 79 (12)	5	56°	20°	170°	115°	45°	164°	959
21 Jan 79 (00)	2	55°	20°	150°	120°	40°	138°	1006
21 Jan 79 (12)	2	57°	21°	158°	128°	40°	148°	1004
22 Jan 79 (00)	2	51°	20°	160°	130°	41°	156°	1001
25 Jan 79 (00)	2	60°	38°	125°	90°	44°	118°	1012
25 Jan 79 (12)	2	60°	30°	144°	100°	42°	130°	1012
26 Jan 79 (00)	2	57°	30°	150°	100°	46°	136°	1007
26 Jan 79 (12)	3	56°	33°	150°	105°	45°	142°	996
27 Jan 79 (00)	3	58°	30°	160°	118°	45°	147°	998
27 Jan 79 (12)	4	54°	20°	166°	120°	45°	153°	991
28 Jan 79 (00)	5	55°	18°	170°	125°	39°	160°	994
29 Jan 79 (00)	2	54°	20°	140°	105°	30°	125°	1008
29 Jan 79 (12)	2	55°	22°	140°	108°	32°	130°	1003
30 Jan 79 (00)	2	56°	20°	144°	110°	34°	139°	1006
30 Jan 79 (12)	2	53°	18°	152°	117°	38°	145°	1000
31 Jan 79 (00)	3	60°	20°	150°	105°	38°	152°	1004
31 Jan 79 (12)	3	58°	20°	150°	104°	37°	158°	1004
1 Feb 79 (00)	3	60°	18°	150°	98°	41°	141°	998
1 Feb 79 (12)	4	60°	19°	153°	105°	46°	146°	990
2 Feb 79 (00)	4	60°	19°	159°	118°	48°	150°	994
5 Feb 79 (00)	1	60°	22°	130°	100°	28°	128°	1016
5 Feb 79 (12)	2	61°	20°	140°	100°	32°	134°	1014
6 Feb 79 (00)	2	62°	18°	152°	106°	36°	143°	1002
6 Feb 79 (12)	3	62°	20°	154°	114°	43°	147°	992
7 Feb 79 (00)	4	63°	20°	162°	105°	46°	148°	986
7 Feb 79 (12)	4	60°	20°	165°	115°	49°	154°	989
8 Feb 79 (00)	4	60°	19°	170°	115°	52°	155°	994
8 Feb 79 (12)	4	60°	20°	170°	120°	57°	152°	1000
9 Feb 79 (12)	2	63°	20°	136°	99°	47°	124°	1008
10 Feb 79 (00)	2	64°	19°	141°	100°	47°	128°	996
10 Feb 79 (12)	3	60°	21°	148°	100°	48°	134°	997
11 Feb 79 (00)	4	58°	22°	153°	104°	49°	139°	980
11 Feb 79 (12)	4	57°	23°	160°	115°	48°	143°	984
12 Feb 79 (00)	4	55°	22°	165°	121°	51°	146°	984
12 Feb 79 (12)	4	55°	23°	170°	126°	52°	152°	994
13 Feb 79 (00)	1	56°	19°	136°	97°	33°	117°	1013
13 Feb 79 (12)	2	60°	18°	144°	103°	41°	132°	1010

Table 1 (continued)

14 Feb 79 (00)	2	60° N	20° N	144° E	108° E	42° N	137° E	1004
14 Feb 79 (12)	3	60°	20°	150°	111°	47°	141°	994
15 Feb 79 (00)	4	58°	22°	154°	110°	49°	143°	989
15 Feb 79 (12)	5	58°	20°	160°	113°	50°	142°	994
16 Feb 79 (00)	5	60°	20°	163°	124°	52°	143°	993
16 Feb 79 (12)	2	51°	20°	140°	109°	37°	125°	1002
17 Feb 79 (00)	2	48°	20°	142°	100°	38°	133°	998
17 Feb 79 (12)	2	53°	18°	155°	107°	37°	141°	997
18 Feb 79 (00)	3	53°	18°	156°	108°	40°	147°	980
18 Feb 79 (12)	4	56°	19°	166°	116°	44°	157°	974
19 Feb 79 (00)	2	52°	20°	157°	121°	46°	146°	998
19 Feb 79 (12)	2	53°	19°	162°	121°	42°	155°	996
20 Feb 79 (00)	3	58°	20°	170°	137°	44°	162°	980
20 Feb 79 (12)	2	60°	35°	144°	98°	50°	136°	1000
21 Feb 79 (00)	2	57°	35°	150°	101°	51°	141°	998
21 Feb 79 (12)	3	61°	31°	157°	117°	54°	148°	990
22 Feb 79 (00)	3	60°	33°	168°	127°	55°	155°	980
22 Feb 79 (12)	4	60°	24°	170°	128°	55°	155°	984
23 Feb 79 (00)	2	42°	16°	140°	90°	34°	132°	999
23 Feb 79 (12)	2	40°	18°	150°	100°	35°	136°	994
24 Feb 79 (00)	2	42°	22°	155°	110°	36°	144°	990
24 Feb 79 (12)	2	40°	17°	166°	110°	36°	146°	989
25 Feb 79 (00)	3	40°	18°	168°	120°	37°	151°	984
25 Feb 79 (12)	3	41°	17°	170°	133°	37°	153°	984
26 Feb 79 (00)	4	53°	20°	142°	93°	50°	134°	996
26 Feb 79 (12)	4	60°	20°	146°	105°	42°	138°	1000
27 Feb 79 (00)	4	57°	21°	153°	102°	35°	143°	988
27 Feb 79 (12)	4	54°	18°	159°	106°	35°	150°	984

Table 2 Gross energy budget for all identified primary systems of cyclonic development during the observation period from surface to 100 mb. [*k*] is in units of 10⁵ J m⁻² and others are in W m⁻².

Pressure layer (mb)	[<i>k</i>]	[∂ <i>k</i> /∂ <i>t</i>]	−[∇⋅ <i>Vk</i>]	−[∂ω <i>k</i> /∂ <i>p</i>]	−[<i>V</i> ⋅∇φ]	[<i>E</i>]
150–100	3.47	0.04	0.57	−0.27	0.66	0.92
200–150	4.47	0.10	0.96	−0.57	1.09	1.38
250–200	4.47	0.17	1.02	−0.50	1.09	1.44
300–250	4.22	0.17	0.46	−0.05	0.56	0.81
400–300	6.57	0.28	0.05	0.07	0.93	0.77
500–400	4.24	0.22	−0.40	0.38	0.74	0.49
700–500	4.14	0.19	−0.65	0.86	0.24	0.26
850–700	1.19	0.06	−0.21	0.31	0.60	0.64
Sfc–850	0.50	0.08	−0.05	−0.06	1.93	1.74
Total	33.26	1.31	1.74	0.17	7.84	8.44

Table 2 indicates a net import of kinetic energy into the system with an export below 500 mb. A downward flux of kinetic energy from above 300 mb towards the mid and lower troposphere is noted, and it is an important source of kinetic energy in the mid troposphere. The strength and the shape of the vertical profiles of generation and dissipation are similar to those consistently found in cyclonic systems (Kung and Baker, 1975).

The energy budgets of the synoptic low regions at individual observation times are grouped according to the established classification of the developmental stages. Table 3 lists the ensemble energy budgets thus obtained for different stages of cyclonic development. Since the energy budgets are grouped without regard to the time continuity of individual observation times in the same group, the time change [∂*k*/∂*t*] is only to balance other terms

Table 3 Composite energy budgets of different stages of cyclonic development.
 $[k]$ is in units of 10^5 J m^{-2} and others are in W m^{-2} .

Synoptic class	Pressure layer (mb)	$[k]$	$[\partial k / \partial t]$	$-[V \cdot \nabla k]$	$-[\partial \omega k / \partial p]$	$-[V \cdot \nabla \phi]$	$[E]$
1 Incipient stage	150-100	4.41	-0.57	-1.25	-1.77	1.65	-0.81
	200-150	5.33	-0.25	-3.24	-0.45	2.64	-0.79
	250-200	5.05	-0.00	-3.63	-0.94	3.00	-1.57
	300-250	4.52	-0.07	-3.11	0.04	2.68	-0.32
	400-300	7.09	-0.42	-4.26	0.81	3.68	0.65
	500-400	4.67	-0.33	-3.36	0.92	1.85	-0.27
	700-500	4.29	0.10	-2.73	1.30	0.73	-0.80
	850-700	1.01	0.18	-0.35	0.68	0.67	0.82
	Sfc-850	0.35	0.13	-0.09	0.23	1.99	2.01
	Total	36.72	-1.23	-22.03	0.82	18.89	-1.09
2 Developing stage	150-100	3.56	0.11	0.40	-0.24	0.54	0.59
	200-150	4.56	0.05	0.74	-0.61	0.96	1.04
	250-200	4.58	0.07	0.69	-0.46	0.82	0.98
	300-250	4.26	0.24	0.16	-0.06	0.65	0.52
	400-300	6.49	0.52	-0.51	-0.25	1.25	-0.03
	500-400	4.17	0.26	-0.84	0.65	0.59	0.15
	700-500	4.03	0.16	-0.86	0.94	0.40	0.32
	850-700	1.10	0.06	-0.19	0.27	0.76	0.78
	Sfc-850	0.43	0.06	-0.05	-0.04	1.69	1.54
	Total	33.18	1.55	-0.44	0.21	7.66	5.88
3 Early mature stage	150-100	3.18	0.08	0.76	-0.15	0.86	1.40
	200-150	4.06	0.28	1.16	-0.61	1.39	1.65
	250-200	4.07	0.44	1.61	-0.38	1.16	1.94
	300-250	3.93	0.39	0.97	0.33	0.13	1.04
	400-300	6.17	0.82	0.67	0.43	0.32	0.60
	500-400	3.99	0.74	0.23	-0.11	0.91	0.29
	700-500	4.00	0.65	-0.11	0.50	0.77	0.51
	850-700	1.17	0.22	-0.13	0.24	0.90	0.79
	Sfc-850	0.48	0.19	-0.03	-0.06	2.00	1.71
	Total	31.05	3.80	5.12	0.18	8.42	9.92
4 Late mature stage	150-100	3.30	0.07	0.96	-0.14	0.29	1.04
	200-150	4.39	0.10	1.70	-0.56	0.55	1.59
	250-200	4.42	0.11	1.63	-0.57	0.81	1.77
	300-250	4.24	-0.04	1.01	-0.32	0.19	0.92
	400-300	6.66	-0.33	1.07	0.28	0.15	1.82
	500-400	4.28	-0.10	0.31	0.18	0.36	0.96
	700-500	4.15	0.02	-0.20	0.88	-0.62	0.04
	850-700	1.25	-0.02	-0.19	0.32	0.16	0.31
	Sfc-850	0.58	0.03	-0.04	-0.12	2.05	1.85
	Total	33.26	-0.16	6.25	-0.05	3.94	10.30
5 Active occluded stage	150-100	3.71	-0.12	1.07	-0.14	1.17	2.23
	200-150	4.86	0.07	2.48	-0.32	1.42	3.50
	250-200	4.79	0.16	2.67	-0.53	1.79	3.76
	300-250	4.65	-0.09	1.56	-0.36	1.04	2.33
	400-300	7.59	-0.25	1.31	-0.67	1.50	2.39
	500-400	5.05	-0.11	-0.00	0.62	1.40	2.13
	700-500	5.12	-0.53	-1.09	1.21	0.07	0.72
	850-700	1.69	-0.29	-0.62	0.38	0.25	0.30
	Sfc-850	0.78	-0.03	-0.14	-0.20	2.71	2.39
	Total	38.24	-1.19	7.23	-0.01	11.34	19.75

in the composite budget and no significance is attached to it. As the synoptic low region always closely surrounds the center of action, these energy values may be, in general, higher than the budgets of larger areas enclosing the storm vicinity (e.g., Smith, 1973), but weaker than smaller areas covering the most active part of the system (Kung, 1977b; Kung and Chan, 1981; Sheu and Smith, 1977).

Several overall features can be noted concerning the energetics of storm development in Table 3. The westerlies in this region in the winter are known for the thick layer of strong jet stream, and this is reflected on the large kinetic energy $[K]$ in the mid and upper troposphere at all stages. Vertical flux convergence of kinetic energy $-\partial\omega k/\partial p$ from the upper layer toward the mid and lower troposphere is a consistent feature of all stages. However, it is most active in the incipient stage, and even the layer above 100 mb acts as a source region for vertical transport. For each stage of storm development, as shown in Table 3, generation $-\mathbf{V}\cdot\nabla\phi$ and dissipation $[E]$ show bimodal vertical profiles as seen in the gross budget. Generation is largest in the incipient stage and decreases toward the late mature and active occluded stages. Through these stages of development the storm area changes from a region of large kinetic energy outflow to a region of significant inflow.

As shown in Table 4, eddy conversion $-\omega'\alpha'$ appears significant in each stage of development with its largest value in the incipient stage. The change in magnitude of $-\omega'\alpha'$ generally reflects that of $-\mathbf{V}\cdot\nabla\phi$. According to Eq. (5) eddy conversion represents the local baroclinic contri-

butions to cross-isobaric generation. For the middle latitude synoptic-scale disturbances over North America for a 5-year period, as computed by Kung (1977a), $-\omega'\alpha'$ was 2.61 W m^{-2} with a corresponding $-\mathbf{V}\cdot\nabla\phi$ value of 7.99 W m^{-2} , yielding the contribution of local baroclinic conversion as 33% of the total generation. In this study the values of $-\omega'\alpha'$ and $-\mathbf{V}\cdot\nabla\phi$ respectively are 6.77 and 7.84 W m^{-2} for all observations (Tables 2 and 4) with 86% of the total generation coming from local baroclinic conversion by eddies. The available studies (e.g., Eddy, 1965; Pettersen and Smebye, 1971) indicate that the storm developments in the middle latitudes depend on the *in situ* latent heat release within the storm systems, which support the strong local baroclinic conversion. In a heat budget study over the Kuroshio region, Kung and Siegel (1979) reported that an enhanced supply of sensible heat and latent heat through the transfer at air-sea interface is associated with significantly increased conversion in amplification of the disturbances. The scale of baroclinic conversion measured in this analysis is defined by the grid scale of $1.874^\circ \times 1.875^\circ$. The pattern of the vertical motion ω described by the data set is as typically observed in the synoptic analysis of the storm system. In the present study no direct estimate of the heat budget is done. However, from the fact that the winter cyclonic development in this region takes place over the warm ocean with an ample supply of heat, it will be reasonable to assume that the heat transfer from the warm water to the cold air may substantially contribute to the very large baroclinic conversion in the storm development. However, this does not rule out the important source of

Table 4 Eddy conversion $-\omega'\alpha'$ in different stages of cyclonic development in units of W m^{-2} .

Pressure layer (mb)	Developmental stage (Synoptic class)					Average of all cases
	1	2	3	4	5	
400-100	4.19	2.41	2.07	1.15	1.72	2.08
700-400	6.38	3.60	3.01	2.31	5.19	3.42
Sfc-700	2.28	1.00	1.39	0.95	2.71	1.27
Total	12.85	7.01	6.47	4.41	9.62	6.77

energy within the circulation to support the amplification of disturbances as reported by Kung (1977b) and Kung and Chan (1981). Indeed the strongest generation in the incipient stage 18.89 W m^{-2} is not totally accounted for by the strong conversion 12.85 W m^{-2} , and the upper troposphere acts as an important energy source as reflected by the significant downward transport of kinetic energy to the mid troposphere, implying the importance of the internal kinetic energy source in the incipient stage.

When a storm is classified in stage 1 (the incipient stage), the surface cyclone often has not yet formed, and frontal systems are just beginning to develop. The systems identified in this stage are usually observed to subsequently develop into strong storms. The observed strong kinetic energy generation has large contributions from the baroclinic processes and also from the internal energy sources as indicated by $-\omega'\alpha'$ and $-\partial\omega k/\partial p$ (Tables 3 and 4). Dissipation $[E]$ is generally negative in this stage, indicating that the sub-grid processes are contributing significantly to the kinetic energy of the incipient storm, and the value of $[E]$ is masked by the large sub-grid scale contribution. Energetically, this is the most active stage in the whole process of cyclonic development.

When a storm is identified in stage 2 (the developing stage), the surface low pressure center has formed and is deepening along with the upper trough. In this stage the intensity of the energetics process appears less than that in the incipient stage. The decrease in $[k]$, however, may be due to the uneven sample numbers in different stages (see Table 1 and Fig. 4) to include weaker, slowly developing systems which are not identified for stage 1. As observed in cyclones in other regions, the balance of kinetic energy is observed largely between $-\mathbf{V}\cdot\nabla\phi$ and $[E]$. In this stage most of the generation $-\mathbf{V}\cdot\nabla\phi$, 7.66 W m^{-2} , is from the eddy conversion 7.01 W m^{-2} . This 92% contribution of eddy conversion to generation in the winter monsoon cyclones marks a sharp contrast to 32% for continental cyclones over North

America in the same stage (Kung, 1977a).

As the surface occlusion begins to form and the surface systems continues to deepen, the storm is in stage 3 (the early mature stage). The inflow of kinetic energy becomes large with a major contribution in the upper troposphere. The increase in generation from stage 2 is small, but there is a significant increase of dissipation in the upper troposphere. Eddy conversion begins to diminish somewhat, reflecting decreased baroclinic conversion due to the diminishing thermal contrast as the cyclones enter their occluded stage. While the system is still deriving energy mainly from the internal source, it is increasingly dependent upon the inflow of kinetic energy from outside the area.

When a storm has attained stage 4 (the late mature stage), it is considered a fully mature cyclone, with a deep, well-occluded surface center and a closed circulation at 500 mb. For more than half of the storm cases this is the highest level of development to be attained. The strength of the energy transformations is expected to have declined, as indicated for occluded cyclones by Kung and Baker (1975) and Masters and Kung (1983). The inflow of kinetic energy into the system further increases to 6.25 W m^{-2} , and becomes the second largest term in the kinetic energy balance, only after 10.30 W m^{-2} for dissipation. Both generation and conversion diminish to around 4 W m^{-2} .

If the systems attain stage 5 (the active occluded stage), they are strongly occluded and have a deep surface low and possibly a strong closed upper-level low over the surface low. These storms possess the highest level of $[k]$, and are the strongest storm systems observed in the region during the FGGE winter. The import of kinetic energy remains approximately the same. However, it is most significant in this stage that both eddy conversion $-\omega'\alpha'$ and generation $-\mathbf{V}\cdot\nabla\phi$ again show a drastic increase. Dissipation reaches the highest level in this stage. This increase in the intensity of energy transformations is obviously different from the weaker processes generally reported for occluded systems in other areas (e. g., Kung and Baker,

1975) and from the stage 4 occlusion of this study. In three out of four cases identified in stage 5, secondary cyclone development was noted along the cold front in the southwest portions of the synoptic low region. While none of these secondary systems developed into major storms, they could account for the increased $-[\mathbf{V} \cdot \nabla \phi]$ and $-\omega' \alpha'$ values in stage 5. A storm without secondary cyclone development in stage 5 does not show an increase of $-[\mathbf{V} \cdot \nabla \phi]$ and $-\omega' \alpha'$.

4. Individual storm systems

To closely examine storms in the winter monsoon, five active cyclones are selected during the data period. The primary systems selected are

Case	Time period	Developmental stage attained				
1	00 GMT 10 Jan.— 12 GMT 11 Jan.	1	3	4	5	
2	12 GMT 17 Jan.— 12 GMT 19 Jan.	1	3	4	5	
3	00 GMT 25 Jan.— 00 GMT 28 Jan.	2	3	4	5	
4	00 GMT 5 Feb.— 12 GMT 8 Feb.	1	2	3	4	
5	00 GMT 13 Feb.— 00 GMT 16 Feb.	1	2	3	4	5.

Each of these systems formed near the coast of China as a pre-existing upper-level short wave moved into the area from the west. The upper-level flow then developed into a deep trough and eventually a closed circulation. The surface system developed to varying degrees and moved northeastward towards the Aleutian low area. The surface centers of the primary cyclones and frontal positions during storm development are illustrated in Fig. 3.

The first two cases were similar in their development and could be considered as classic winter monsoon cyclones. In each case strong, cold high pressure was initially centered north of the Tibetan Plateau and extended over much of China. A low pressure trough formed off the coast, and then developed a medium-scale cyclone and frontal system which deepened rapidly as it moved to the

northeast. A strong push of cold air swept across the western Pacific as the storm matured. Aloft, the jet stream intensified over eastern China and southern Japan, attaining maximum speeds at the peak of development. Eventually, the initial upper-level short wave developed into a deep cut-off low. These two cases were the only storm systems with strong cold outbreaks to form in this area during the FGGE winter. These two cases were grouped together as "Type I" storms.

Cases 3, 4 and 5 were weaker aloft and considerably more disorganized at the surface. The cold air outbreak during each of these storms was rather weak. The surface development of these systems was characterized by relatively shallow, multiple low centers and frontal systems. The upper air development, while not as strong as the first two cases, still formed a deep trough and a closed upper circulation. These weaker cases also proceeded through their development cycles at a much slower pace. These three storms are identified as "Type II."

For each of the five cases, the energy budgets of the defined synoptic low region are averaged over the lifetime of the storm as shown in Tables 5 and 6. Cases 1 and 2 stand out as clearly having a higher kinetic energy level $[k]$ than the others, each case averaging a third more kinetic energy than any of the other cases. This contrast reflects a difference in the orientation of the synoptic low region with respect to the jet stream. These two cases also export kinetic energy, whereas the other three cases show a net inflow of kinetic energy into the system. Export of kinetic energy $-\nabla \cdot \mathbf{V}k$ by the former two cases is particularly significant in the incipient stage of development when both generation $-\mathbf{V} \cdot \nabla \phi$ and eddy conversion $-\omega' \alpha'$ are at their maximum (Fig. 4).

The variation of $-\mathbf{V} \cdot \nabla \phi$ during storm development, as in Fig. 4, also shows a distinction between the first two cases and the other three. The former cases have high generation values early in their development, with a decrease as the storm matures. The latter cases show a minimum in the develop-

Fig. 3 Sequential development of primary systems as shown by the sea level center pressure (mb) and frontal position.

ing stage with an increase in the active occluded stages.

As discussed earlier, eddy conversion $-\omega'\alpha'$ is the most important process for cyclonic development over the ocean to sustain generation $-\mathbf{V}\cdot\nabla\phi$ in the system. However, there is no clear distinction between the first and second group of cases for this term

(Fig. 4). Comparing the case mean values of $-\omega'\alpha'$ in Table 6 and the storm paths of Fig. 3, it is apparent that the amount of baroclinic conversion $-\omega'\alpha'$ depends on the location of the storm development. The case 2 system started to develop off the coast of Japan where the Kuroshio most effectively warms up the cold air. After its incipient

Table 5 Mean energy budgets for five selected cases of primary systems.
[k] is in units of 10^5 J m^{-2} and others in W m^{-2} .

Storm case	Pressure layer (mb)	[k]	$[\partial k / \partial t]$	$-[\nabla \cdot \nabla k]$	$-\partial \omega k / \partial p$	$-\nabla \cdot \nabla p$	[E]
1 00 GMT 10 Jan- 12 GMT 11 Jan	150-100	4.15	0.19	0.87	1.35	1.42	0.76
	200-150	5.08	0.38	0.08	-0.18	3.33	2.84
	250-200	4.82	0.32	-0.73	-0.10	3.82	2.66
	300-250	4.47	0.11	-0.70	-0.93	3.41	1.67
	400-300	7.77	-0.10	-1.65	0.26	5.59	4.29
	500-400	5.74	-0.04	-2.87	1.39	3.42	1.99
	700-500	5.84	0.33	-3.36	1.06	1.83	-0.80
	850-700	1.70	0.19	-0.49	0.75	1.14	1.20
	Sfc-850	0.71	0.13	-0.03	-0.19	4.16	3.81
Total		40.28	1.52	-8.90	0.70	28.12	18.41
2 12 GMT 17 Jan- 12 GMT 19 Jan	150-100	4.72	-0.13	-0.68	-1.14	1.66	-0.03
	200-150	5.82	0.16	0.37	-0.27	0.51	0.45
	250-200	5.63	0.28	1.15	-0.27	0.35	0.95
	300-250	5.30	0.18	0.65	-0.04	0.07	0.50
	400-300	8.58	0.39	-0.54	0.84	-0.12	-0.22
	500-400	5.54	0.41	-1.57	0.06	0.43	-1.49
	700-500	5.20	0.27	-1.41	1.24	0.69	0.25
	850-700	1.56	0.08	-0.45	0.19	1.01	0.67
	Sfc-850	0.64	0.13	-0.14	-0.04	3.07	2.76
Total		42.99	1.77	-2.62	0.57	7.66	3.85
3 00 GMT 25 Jan- 00 GMT 28 Jan	150-100	3.11	-0.22	0.89	-0.55	-0.01	0.55
	200-150	3.99	-0.09	1.19	-1.05	1.28	1.51
	250-200	4.11	0.04	1.82	-1.00	0.60	1.39
	300-250	3.92	0.13	1.20	-0.46	0.14	0.74
	400-300	6.32	0.27	0.41	0.05	0.48	0.68
	500-400	4.23	0.36	0.18	0.95	0.54	1.31
	700-500	3.99	0.31	-0.38	2.03	-0.20	1.14
	850-700	1.08	0.04	-0.20	0.20	-0.26	-0.29
	Sfc-850	0.44	0.11	-0.05	0.25	1.50	1.59
Total		31.18	0.95	5.07	0.43	4.07	8.61
4 00 GMT 05 Feb- 12 GMT 08 Feb	150-100	3.85	-0.41	0.40	-0.29	1.10	1.62
	200-150	4.42	-0.37	0.55	-1.09	1.97	1.80
	250-200	4.19	-0.40	0.41	-0.82	1.73	1.72
	300-250	3.84	-0.41	-0.11	0.37	-0.05	0.62
	400-200	5.61	-0.43	0.45	0.84	-1.44	0.28
	500-400	3.37	-0.21	0.34	0.31	-1.12	-0.26
	700-500	3.11	-0.22	0.07	0.62	-1.35	-0.46
	850-700	0.87	-0.06	-0.05	0.31	0.55	0.86
	Sfc-850	0.35	-0.01	-0.01	-0.06	1.23	1.17
Total		29.62	-2.52	2.06	0.18	2.62	7.37
5 00 GMT 13 Feb- 00 GMT 16 Feb	150-100	2.74	0.13	-0.19	0.79	0.82	1.29
	200-150	3.92	0.19	0.43	0.15	1.28	1.67
	250-200	3.86	0.36	1.08	-0.34	2.20	2.58
	300-250	3.91	0.29	0.11	1.25	1.19	2.26
	400-300	6.27	0.33	-0.72	-0.37	1.50	0.08
	500-400	3.90	0.31	-0.04	-0.84	1.82	0.63
	700-500	3.80	0.42	-0.17	-0.75	0.46	-0.89
	850-700	1.06	0.18	-0.16	-0.26	0.41	-0.19
	Sfc-850	0.41	0.09	-0.02	-0.10	1.48	1.27
Total		29.89	2.30	0.33	-0.47	11.16	8.72

Table 6 Mean eddy conversion $-\langle\omega'\alpha'\rangle$ for five selected cases of primary systems in units of W m^{-2} .

Pressure layer (mb)	Case				
	1	2	3	4	5
400-100	2.73	1.76	0.33	2.98	2.80
700-400	2.15	6.99	1.52	2.03	2.97
Sfc-700	0.20	3.87	0.46	-0.46	1.42
Total	5.08	12.63	2.32	4.55	7.19

Fig. 4 Comparison of developmental stages between two types of storms. Type I is for cases 1 and 2, and type II is for cases 3, 4, and 5.

stage was recognized at 12 GMT 17 January 1979, it quickly developed into the early mature stage 12 hours later and soon reached the active occluded stage, which lasted longer than in other cases (Table 1). Throughout its development the system stayed in the relatively low latitudes over a large area of the western Pacific where the supply of latent heat was abundant. As seen in Table

6, this case converted the largest amount of eddy energy, 12.63 W m^{-2} , through local baroclinicity which is significantly larger than the generation of this case, 7.66 W m^{-2} (Table 5). On the contrary, the case 3 system only converted 2.32 W m^{-2} , although this is 89% of its generation (2.62 W m^{-2}). In this case the development of the system was slow with the center of action east of Japan. Only after it reached Japan, or its major portion entered the western Pacific, did the system begin to show maturing. Even then the center pressure was not as deep as for the other cases. Obviously, a smaller latent heat supply restricted development of the system through less local baroclinic conversion and consequently less kinetic energy generation.

The conversion of case 4 and 5 systems is between that of cases 2 and 3. Cases 4 and 5 developed with a more local supply of latent heat over the western Pacific than case 3, but less than case 2. In both cases 4 and 5, generation is wholly dependent on local baroclinic conversion. The generation of the case 1 system is the highest of all cases with 28.12 W m^{-2} . However, conversion in this case is 5.08 W m^{-2} , a significant amount but much less than its generation. It requires a significant contribution from $-\langle\nabla \cdot V\phi\rangle$ and/or $-\langle\omega\rangle\langle\alpha\rangle$ (see Eq. 5)—both terms are interpreted as the supply of energy from the system whose scale is larger than or equal to that of the storm concerned. This indicates that, in the rapid development of major storms associated with a strong cold outbreak, it is possible that a large energy source within the winter monsoon can be released along with local baroclinic conversion to maintain the large kinetic energy generation required during storm development.

5. Concluding summary

The composite energy budgets of the primary storm systems in the winter monsoon show characteristic energetics features in the various stages of development from their inception to occlusion. The level of kinetic energy is high throughout all developmental stages, reflecting the thick layers of strong jet stream in this region. In the winter

monsoon the significant vertical flux convergence from the upper layer toward the mid and lower troposphere is a consistent feature through all stages. In the incipient stage of the storm, generation of kinetic energy $-[V \cdot \nabla \phi]$ is very high. There is an additional supply of kinetic energy from the smaller than observed scales in this stage. Generation decreases towards the late mature stage, but again intensifies significantly when the storm reaches the active occluded stage. Dissipation increases from the insignificant value of the incipient stage to very large values in the occluded stage. Initially, the storm system exports a large amount of kinetic energy, but it becomes an area of significant inflow in the latter stages.

Eddy conversion $-[\omega' \alpha']$ is the largest source of kinetic energy generation in the winter monsoon storm, which is consistent with the fact that the cyclonic growth takes place over the ocean which is warmer than the air. This strong local baroclinicity in the primary systems differs significantly from the cyclones observed over the continental areas where the contribution of $-[\omega' \alpha']$ is rather limited. There is also an additional energy source within the system of circulation as evidenced by the transport of kinetic energy from the upper to mid troposphere.

Upon examination of the five selected storm systems, it appears there are two types of developmental sequences. Type I storms which are accompanied by strong cold outbreaks follow the classical cyclone development from initial trough and frontal zone formation to a deep occluded system. This storm system is characterized by a high level of kinetic energy, and generally a high level of transformation in the earlier stages of development. The system exports kinetic energy to the surrounding. The type II storm, more common during the 1978-1979 winter, was weak and disorganized at the surface with the cold air outbreak being weak or non-existent. Energy generation in this type of storm is weak in the early developmental stage with an increase in the active occluded stage. Despite the clear difference in other energy variables between these two types,

there is little distinction between them in eddy conversion. The difference in $-[\omega' \alpha']$ among storm cases appears to depend on the storm path rather than on type, with the largest local baroclinic contribution found in cases of rapidly developing storms over the warm ocean.

An attempt is made in this study to include all observed primary systems during the data period. However, the uneven sample size of various developmental categories is unavoidable because of individual differences among storm cases. Many of them are not identified in stages 1 and 5. Thus a bias in the composite energy budgets is inevitable. Yet, it is our belief that the essential description of energetics processes in this study is correct through careful examination of individual cases.

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アジア冬期モンスーンにおける低気圧発達のエネルギー解析

Stephen E. Masters* and Ernest C. Kung

アジア大陸から西太平洋に至る冬期アジアモンスーンにおける低気圧の発達に関し、FGGE年についてエネルギー変換過程を調べた。数値解析は個々の Storm の発生から移動を追って解析領域を動かして行なった。Storm の発達の様相を合成的に見るために、エネルギー収支は発達の各ステージ毎にわけてまとめた。また5例については個別的な解析も示してある。

運動エネルギーの生成は、その大部分(86%)が渦による局所的な傾圧性に起因するものである。これは、低気圧の発達が海洋上で起っているという事実と合致している。しかし、Storm 組織内部には更に附加的なエネルギー源も存在する。Eddy Conversion の総量は Storm の経路にも依存する: すなわち変換量が最大となるのは、暖い海洋上の広域にわたって Storm が急速に発達する場合である。運動エネルギーの強さとバランスは、Storm の初期の段階から発達末期の閉塞段階にかけて急激に変化する。初期には運動エネルギーの生成と放出が最大であり、消散は最小である。これに対し、発達の後期には、生成と放出は減少し、消散が明瞭に増大する。後期においては、運動エネルギーが大量に系外から補給されている。

* 現在所属: ENSCO, Inc., Indian Harbour Beach, Florida 32937.