strated conclusively that the mineralogy of the E, R, P, and D asteroids is consistent with this theory.

In conclusion, the asteroid belt is sorted into at least six compositionally distinct regions. It seems unlikely that the gross features of this distribution can be explained by the random transport of objects over large distances from other regions of the solar system; rather it appears that the asteroids formed at or near their present locations. When determined, the detailed chemical composition of the asteroids in each region can be used to provide constraints on the small-scale thermodynamic conditions of the solar nebula in the transition region between the terrestrial and Jovian planets.

J. GRADIE
Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853

E. TEDESCO*
Lunar and Planetary Laboratory, University of Arizona, Tucson 84721

References and Notes

1. J. W. Larimer, *Geochim. Cosmochim. Acta* **31**, 1215 (1967); J. S. Lewis, *Icarus* **16**, 241 (1972); L. Grossma and J. W. Larimer, *Rev. Geophys. Space Phys.* **12**, 71 (1974).
2. J. T. Wasson and G. W. Wetherill, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 926; C. R. Chapman, in *ibid.*, p. 25; G. W. Wetherill, in *Comets, Asteroids, Meteorites*, A. H. Delsemme, Ed. (Univ. of Toldeo Press, Toledo, Ohio, 1977), p. 283.
3. C. R. Chapman, D. Morrison, B. Zellner, *Icarus* **25**, 104 (1975).
4. B. Zellner and E. Bowell, in *Comets, Asteroids, Meteorites*, A. H. Delsemme, Ed. (Univ. of Toledo Press, Toledo, Ohio, 1977), p. 185; B. Zellner, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 783.
5. "Tucson revised index of asteroid data," B. Zellner, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 783.
6. J. Degewij and C. J. van Houten, in *ibid.*, p. 147.
7. E. Tedesco and J. Gradie, in preparation.
8. E. Anders, in "Asteroids: An exploration assessment," D. Morrison and W. C. Wells, Eds., *NASA Conf. Publ. 2053* (1977), p. 2053.
9. D. Morrison and B. Zellner, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 1090.
10. E. Tedesco, D. Tholen, B. Zellner, in preparation.
11. T. Kiang, in "Physical studies of minor planets," T. Gehrels, Ed., *NASA Spec. Publ. SP-267* (1971), p. 187.
12. J. Gradie, thesis, University of Arizona, Tucson (1978); E. Tedesco, thesis, New Mexico State University, Las Cruces (1979); J. Gradie, C. R. Chapman, J. G. Williams, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 359.
13. J. G. Williams, in *Asteroids*, T. Gehrels, Ed. (Univ. of Arizona Press, Tucson, 1979), p. 1040.
14. M. J. Gaffey and T. B. McCord, in *ibid.*, p. 688.
15. J. Gradie and J. Veverka, *Nature (London)* **283**, 840 (1980).
16. B. Zellner, M. Leake, D. Morrison, J. G. Williams, *Geochim. Cosmochim. Acta* **41**, 1759 (1977).
17. The authors were visiting astronomers at the Infrared Telescope Facility, which is operated by the University of Hawaii under contract from the National Aeronautics and Space Administration. This work was supported in part by grants from the Planetary Geosciences and Planetary Astronomy and Atmospheres branches of NASA. We thank C. R. Chapman and E. Anders for suggestions and advice.
* Present address: Jet Propulsion Laboratory, California Institute of Technology, Pasadena 91109.

20 November 1981; revised 22 March 1982

Low-Frequency Eddy Kinetic Energy Spectrum in the Deep Western North Pacific

Abstract. *The frequency spectrum for the low-frequency eddy kinetic energy is estimated from a long-term current meter record obtained in a deep layer in the western North Pacific. The eddy field is characterized by three time scales: an "annual scale" with zonal dominance of eddy motions, a "temporal mesoscale" with meridional dominance, and a "monthly scale" with horizontal isotropy. About two-thirds of the eddy kinetic energy is contained in the temporal mesoscale.*

Mid-ocean mesoscale eddies, either barotropic or baroclinic, seem to exist all over the world ocean, having typical time scales of weeks to months and typical horizontal scales of tens to hundreds of kilometers (*1*). Intensive observational studies of the eddies have been made, most of them in the western North Atlantic (*1*, *2*). Year-long current measurements have been made there and frequency spectra for the low-frequency fluctuations (frequencies less than one cycle per day) have been estimated (*3*, *4*). Several studies of the mesoscale eddies in the Pacific have been based on temperature and salinity measurements (*5*), but very few studies have been based on direct current measurements (*6*). We report here, for the first time, the spectral features of the low-frequency fluctuations, including the annual fluctuations, in the mid-ocean of the western North Pacific on the basis of a long-term current meter record.

A program of long-term deep current measurements by moored meters was started in October 1978 in the western North Pacific as a part of a preoperational survey of a proposed area for the disposal of low-level radioactive wastes. It is expected to continue over several years. The observation site is centered at 30°N, 147°E in the mid-ocean; it is about 500 km south of the Kuroshio Extension and about 400 km east of the Izu-Ogasawara Ridge. The water depth is about 6200 m, and the bottom topography is fairly flat with no pronounced slopes; the water depth varies from about 6000 to 6400 m within 100 km of the site center. The most prominent topographic feature is a small hill with a depth of 4890 m, located about 30 km north of the site center. The existence of low-frequency velocity fluctuations near the site was suggested by an earlier current measurement made over a period of about 3 months (*7*).

The mooring lines have been deployed and recovered four times at several stations. From these measurements, a continuous current meter record for 1020 days has been obtained in the deep layer at station RB, whose nominal position is 30°00′N, 147°08′E. It is the longest current meter record ever obtained in the mid-ocean of the world ocean (*8*). Aanderaa RCM-5 current meters were used.

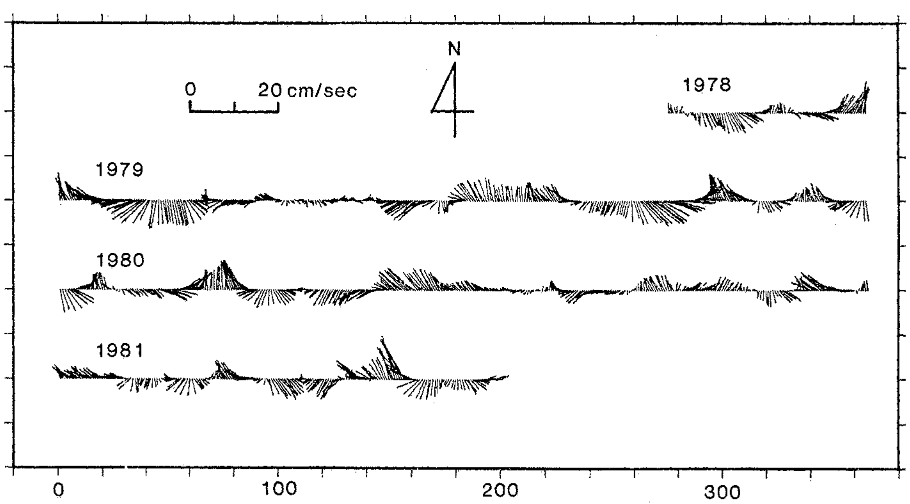

Fig. 1. Time series of daily mean current velocity observed at a nominal depth of 5000 m in the western North Pacific (30°00′N, 147°08′E) from 3 October 1978 to 18 July 1981. Each stick represents the daily current vector (upward north). The record from year day 327 in 1979 to year day 236 in 1980 was not obtained. Here it is justifiably made up for by a record at a nominal depth of 4000 m at the same station, because no significant differences in daily mean velocities between nominal depths of 4000 and 5000 m are recognized at that station or at the other stations at the site (*10*).

0036-8075/82/0625-1407$01.00/0

Most of the data were sampled at intervals of an hour. Diurnal and semidiurnal fluctuations distinctly emerge from the raw data. The data are averaged over 1 day for an analysis of the low-frequency fluctuations; the period of the local inertial oscillations at the site is 23.9 hours. Figure 1 illustrates the time series of daily mean velocity at a nominal depth of 5000 m at station RB. Low-frequency fluctuations are clearly seen.

The zonal velocity component averaged over the record length is -0.6 cm/sec (positive eastward), and the meridional one is 0.3 cm/sec (positive northward), giving a kinetic energy per unit mass for the mean flow of 0.2 cm^2/sec^2. (The per unit mass is hereafter understood.) This very weak mean flow is an indication that the site is located at the mid-ocean. The zonal kinetic energy for the low-frequency motions is about 3.2 cm^2/sec^2 and the meridional one is 3.6 cm^2/sec^2, giving a total kinetic energy for the low-frequency motions of 6.8 cm^2/sec^2. The total kinetic energy for the low-frequency motions is fairly large and about an order of magnitude greater than the kinetic energy for the mean flow.

The present long-term record gives statistically significant estimates of frequency spectra for these low-frequency eddy kinetic energies. Figure 2 shows spectra for the zonal, meridional, and total eddy kinetic energies in a variance-preserving form. The spectra are estimated from energy densities obtained by the fast Fourier transform method and averaged over eight frequencies. Hence the spectra for the zonal and meridional kinetic energies are regarded as containing 16 degrees of freedom, and their 95 percent confidence limits are from 0.55 to 2.32 times the individual estimates. The spectrum for the total eddy kinetic energy is regarded as containing more than 16 degrees of freedom, and its confidence limits are somewhat narrower than those of the zonal and meridional kinetic energies.

For convenience, each spectrum is divided into four frequency bands (Fig. 2). Band 1, ranging from 120- to 2040-day periods, is tentatively labeled an "annual scale." Band 2, ranging from 31- to 120-day periods, is labeled a "temporal mesoscale," according to Schmitz (*3*). The total eddy kinetic energy is largest in the temporal mesoscale; this scale contains about two-thirds of the whole eddy kinetic energy, and might be called an energy-containing band (*1*) or an eddy-containing band (*4*). There, the meridional eddy kinetic energy is larger than the zonal eddy kinetic energy; the former is about twice as large as the latter for this record. In the annual scale, on the other hand, the zonal eddy kinetic energy is much larger than the meridional eddy kinetic energy. Zonal dominance of eddy motions in such low-frequency eddy fields is also suggested by theoretical work (*9*).

Both zonal dominance of eddy motions in the annual scale and meridional dominance in the temporal mesoscale can be accounted for qualitatively by the phase propagation direction of the Rossby wave with a moderate wavelength; the Rossby wave whose phase propagation is directed nearly parallel to the meridian has a long period and the associated motion is dominantly zonal, whereas the Rossby wave whose propagation is directed near to the west has a shorter period and the associated motion is dominantly meridional.

In band 3, ranging from 16- to 31-day periods, tentatively labeled a "monthly scale," the zonal and meridional eddy kinetic energies are almost equal to each other, an indication that the eddy field is horizontally isotropic in this scale. It might be remarked that a considerable part of the kinetic energy in this scale should come from a frequency band between 21- to 25-day periods, although it is not significant with 95 percent confidence levels. In band 4, ranging from 2- to 16-day periods, the eddy kinetic energies are trivially small.

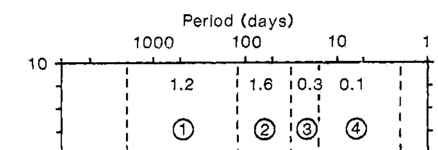

Fig. 2. Decadal frequency (ν) spectra for the low-frequency eddy kinetic energy (K_E) per unit mass estimated from the record shown in Fig. 1, plotted in a variance-preserving form. The top spectrum is the zonal eddy kinetic energy spectrum, the middle spectrum the meridional one, and the bottom spectrum the total one. Numerals indicate the energies contained in individual frequency bands, whose ranges are shown by dashed lines and whose reference numbers are the circled numerals at the top.

The above-mentioned features of the low-frequency fluctuations in the deep layer are also shown in the spectra from a depth of 4000 m in the western North Atlantic, although zonal dominance in the annual scale is not definitely indicated (*3*, *4*, *8*). They are probably common features of the eddy field in the deep layer of the world ocean.

With respect to the annual scale, current meter records available to date have not been long enough. The present long record enables us, for the first time, to make statistically significant spectral estimates of the low-frequency eddy kinetic energy in this scale.

S. IMAWAKI

Geophysical Institute,
Kyoto University,
Kyoto 606, Japan

K. TAKANO

Institute of Biological Sciences,
University of Tsukuba,
Sakura-mura, Ibaraki 305, Japan

References and Notes

1. MODE Group, *Deep-Sea Res.* **25**, 859 (1978).
2. M. N. Koshlyakov and Y. M. Grachev, *ibid.* **20**, 507 (1973).
3. W. J. Schmitz, Jr., *J. Mar. Res.* **36**, 295 (1978).
4. J. G. Richman, C. Wunsch, N. G. Hogg, *Rev. Geophys. Space Phys.* **15**, 385 (1977).
5. R. L. Bernstein and W. B. White, *J. Phys. Oceanogr.* **4**, 613 (1974); *ibid.* **7**, 123 (1977); G. I. Roden, *ibid.*, p. 41; K. E. Kenyon, *J. Geophys. Res.* **86**, 6115 (1978); W. S. Wilson and J. P. Dugan, *J. Phys. Oceanogr.* **8**, 537 (1978); T. P. Barnett and W. C. Patzert, *ibid.* **10**, 529 (1980).
6. S. P. Hayes, in *Marine Geology and Oceanography of the Pacific Manganese Nodule Province*, J. L. Bischoff and D. Z. Piper, Eds. (Plenum, New York, 1979), p. 83; B. A. Taft, S. R. Ramp, J. G. Dworski, G. Holloway, *J. Geophys. Res.* **86**, 1955 (1981); K. Wyrtki *et al.*, *Science* **211**, 22 (1981).
7. S. Imawaki, K. Taira, T. Teramoto, in preparation.
8. C. Wunsch, in *Evolution of Physical Oceanography*, B. A. Warren and C. Wunsch, Eds. (MIT Press, Cambridge, Mass., 1981), p. 342.
9. P. B. Rhines, in *The Sea: Ideas and Observations on Progress in the Study of the Seas*, vol. 6, *Marine Modeling*, E. D. Goldberg, I. N. McCane, J. J. O'Brien, J. H. Steele, Eds. (Wiley, New York, 1977), p. 189; G. Holloway and M. C. Hendershott, *J. Fluid Mech.* **82**, 747 (1977); L.-L. Fu and G. R. Flierl, *Dyn. Atmos. Oceans* **4**, 219 (1980).
10. S. Imawaki and K. Takano, in preparation.

11. The mooring buoy technology was learned on a Woods Hole Oceanographic Institution mooring operation cruise of R.V. *Chain*, in which one of us (S.I.) participated. K. Bradley provided valuable guidance.

11 February 1982; revised 1 April 1982