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Ocean Transients as Observed by Geos 3 Coincident Orbits

A. L. GORDON AND T. N. BAKER

Lamont-Doherty Geological Observatory of Columbia University
Palisades, New York 10964

Ocean mesoscale transients are revealed in Geos 3 altimeter data. The transients are brought out by inspection of the differences within groups of coincident orbits in the western subtropical North Atlantic Ocean. Each of the five groups, used in the study, is composed of three individual Geos 3 orbits, lying within 2 km of the mean orbit of the group. The difference of each orbit from the group mean contains sea level transients and instrumental noise; the steady state geoid is removed. The noise dominates the spectrum below 200 km wavelength, whereas ocean mesoscale transient features dominate above 200 km. At the low frequency end of the spectra the time separation of the individual orbits may attenuate the signal of the long wavelength transients.

The total relief of the mean climatic sea level is approximately 2.0 m (relative to 1000 dbar [*Stommel,* 1965]). Superimposed on mean sea level, which defines the mean horizontal currents by the geostrophic relation, are tides and more slowly varying sea level transients, which may be conceptualized as eddies [*Mode Group,* 1978; *Düing,* 1978]. The non-tidal sea level features with spatial scales from the Rossby radius to a scale small compared to the large scale gyre circulation (roughly 100–1000 km) are considered the mesoscale. The associated mesoscale circulation is also in near geostrophic balance. Some mesoscale features may be in steady state, so are not necessarily transients, nor are all transients mesoscale, in that the seasonal variation of the large gyres are not mesoscale in size. In this study we are concerned with transient mesoscale features.

Wyrtki [1975] shows the fluctuations in dynamic height of the sea surface relative to 500 dbar, superimposed on the seasonal scale variations, are typically 10 dynamic centimeters (dy cm) or more in the western North Pacific, dropping to about 6 dy cm in the east. Using Ocean Station time series data, Wyrtki shows standard deviation in the monthly dynamic height in the western North Pacific at *Victor* (34°N, 164°E) varies between 10 and 20 dy cm, while further east at *November* (30°N, 140°W) standard deviation drops to less than 5 dy cm.

Bernstein and White [1974, 1977], *Dantzler* [1976, 1977], and *Roden* [1977] also show the transients in the western region of the subtropical gyre to be more energetic than those of the east. *Kim and Rossby* [1979] suggest that the higher transient level in the west may be associated with spin-off eddies of the western boundary current, superimposed on the mesoscale transients characteristic of the ocean interior.

Analysis of ship drift data from merchant ships by *Wyrtki et al.* [1976] indicates the mean kinetic energy is about equal to the eddy kinetic energy in the western margins of the subtropical gyres, but less than one tenth of the eddy kinetic energy in the central and eastern regions of the subtropical gyre.

This is similar to the results of *Roden* [1977]. Roden, using hydrographic data in the North Pacific, shows the transient baroclinic flow relative to 1500 dbar is about 10 times that of the mean flow. The dynamic height expression of the transients, described by *Roden* [1977], peak to trough, range from 10 to 30 dy cm, with a wave length of 400–600 km. *Bernstein and White* [1974], studying the isotherm topography observed by expendable bathythermograph traces, find the predominant horizontal scale west of 170°W in the North Pacific is near 900 km, closer to 600 km in the east.

The dynamic height range and horizontal scale associated with the Mode mesoscale feature observed during the Mode project is about 20–30 dy cm and between 400 and 500 km, respectively (*Mode-I Atlas Group* [1977], Figure 2.7—sea surface dynamic topography relative to 1500 dbar; also see *Voorhis et al.* [1976] and *Dantzler* [1976]—note the structure function peak at 200–250 km in Dantzler's Figure 7 corresponds to half of the predominant length scale and apparently drifted westward at typical velocities of 2–3 km/day [*Mode Group,* 1978]).

The object of this study is to determine if the satellite radar altimeter of Geos 3 can be used to study the statistics of sea level mesoscale transients. *Huang et al.* [1978] have shown the Geos 3 altimeter detects Gulfstream spin-off eddies.

THE DATA

Geos 3, launched in April 1975 in an orbit carrying it to 62° latitude, possesses a radar altimeter [*Leitao et al.,* 1975]. The altimeter pulse, emitted by the satellite each 0.1 s (intensive mode), is reflected from the ocean surface back to the satellite. The return pulse, elongated by the varied surface shape due to waves within the 4 km footprint of the pulse, is used to obtain the altitude of the satellite above the local mean ocean surface.

Knowledge of the distance between the orbit and the earth's reference spheroid, determined independently, allows determination of the difference between sea surface and spheroid. Removal of geoid determines the sea level height. Variation in the sea level relative to the geoid includes mean and transient circulation, tides, and atmospheric effects.

The uncertainty in the geoid shape and orbital errors (distance above the spheroid) are larger than the variations in sea level; in addition, the random pulse by pulse noise of the Geos 3 altimeter is about 72 cm [*Martin and Butler,* 1977]. Hence it is not possible to use Geos 3 to directly determine the sea level shape relative to the geoid to high enough accuracy to study specific transient events. As shown below the statistical characteristics of the larger transients are revealed when differences of coincident orbits are considered.

DATA PROCESSING METHODS

Orbits were selected that were nearly coincident in position. In each group all of the orbits are less than 2 km. from the mean orbit for the group. The groups used in this study are

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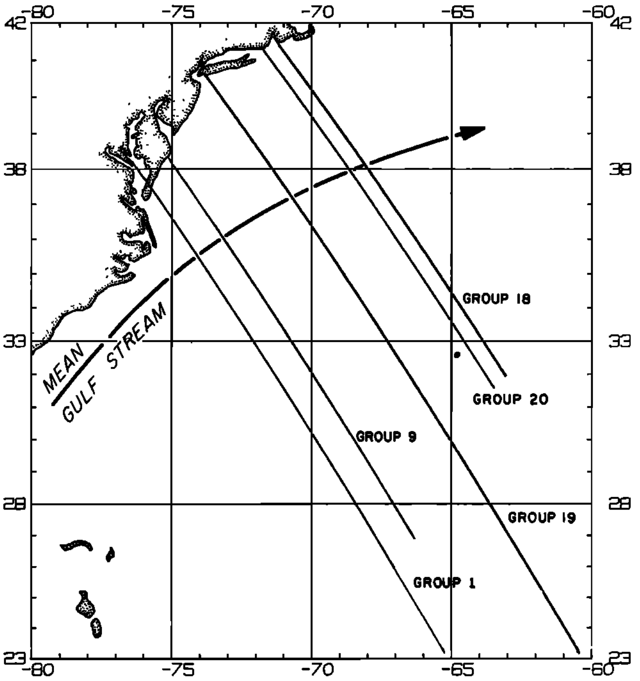

Fig. 1. Position of the five groups of orbits, each composed of three individual orbits (see Table 1), used in this study.

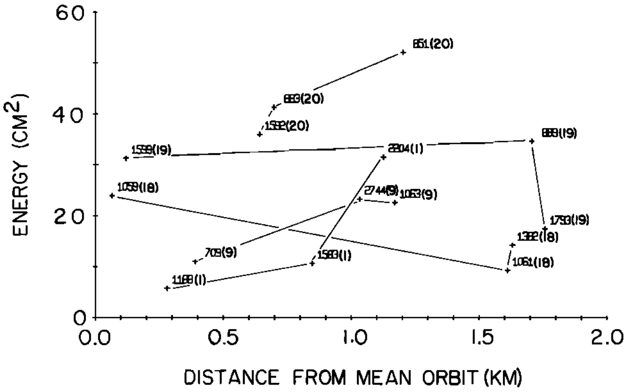

Fig. 2. Total spectral energy for each orbit of each of the five groups as function of distance from the mean position of the group.

given in Figure 1 and Table 1. All groups have 3 orbits. The raw data contained spikes (more than 2 m difference from the previous good point, spikes are generally composed of 5 points or less) which were removed by linear interpolation between the good data points immediately adjacent to the spike. All orbits used were sampled with the satellite operating in the intensive mode, which collected data at the rate of one sample every 0.1 s. That resulted in a spacing of data points slightly greater than 0.69 km. Each raw orbit was then low-pass filtered using an *Ormsby* [1961] convolution filter designed to pass wavelengths greater than 10 km. The low-passed orbits for each group were then averaged to produce a mean orbit for that group. This mean orbit was then subtracted from each low-passed individual orbit in the group to produce residuals which would contain only ocean transients and instrumental noise. We believe that this method removes virtually all of the geoid from the data since variations in the geoid on a scale of 2–4 km are minor. This is supported by Figure 2, which is a plot of the total energy in the spectrum of each orbit versus distance of each orbit from the mean orbit position for that group. This figure shows no systematic increase in energy with increasing distance from the mean orbit position, which would have been the case if the differences are due to residual geoid effects.

Spectra were calculated from the residuals by a version of the *Cooley and Tukey* [1965] fast Fourier transform algorithm. Before transforming, the mean and linear trend were removed from each set of residuals by a least squares straight line fit. A linear trend in the data (if present) can add unwanted energy to the low wavenumber portion of the spectra in addition to the energy occurring at low wavenumbers due to truly periodic fluctuations. Possible sources of trends in the sea level residuals are the long wavelength variations introduced by tracking errors, tides and atmospheric weather systems. These have been removed to enable inspection of quasi-geostrophic mesoscale transients of sea level. In the wavenumber domain, spectra were smoothed with a Hanning spectral window [*Blackman and Tukey*, 1958, p. 98].

Results

The residuals of the individual orbits from the group mean for Group One (Figure 3) show high frequency variation su-

TABLE 1. Groups Used in This Study

Group Number	Orbit Number	Date	Time Spacing, days	Time of Latest Orbit Minus Time of Earliest Orbit, days
1	1188	Oct. 8, 1975	37	320
1	1583	Nov. 14, 1975		
1	2204	Aug. 24, 1976		
9	1063	Sept. 29, 1975	37	320
9	0709	Nov. 5, 1975		
9	2744	Aug. 15, 1975		
18	1382	Aug. 14, 1975	37	75
18	1059	Sept. 21, 1975		
18	1061	Oct. 28, 1975		
19	1793	Aug. 18, 1975	37	112
19	0889	Nov. 1, 1975		
19	1599	Dec. 8, 1975		
20	0851	Sept. 6, 1975	37	75
20	0883	Oct. 14, 1975		
20	1592	Nov. 20, 1975		

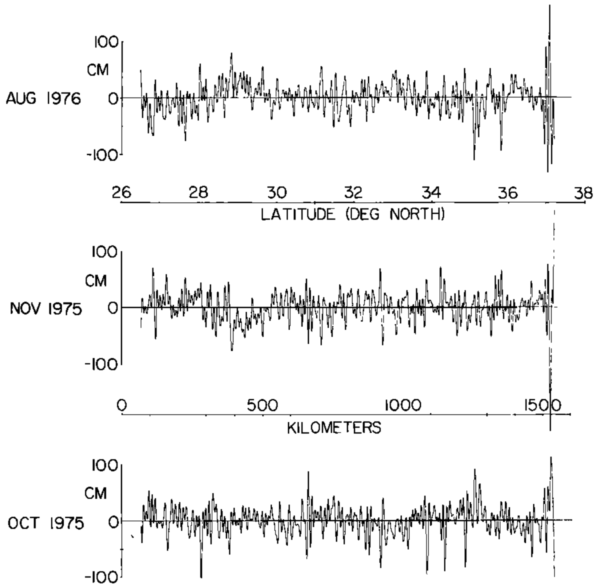

Fig. 3*a*. Sea level difference of each orbit of Group 1 from the mean of Group 1.

perimposed over long wave length variations in sea level. Peak to trough sea level variation is about 40 cm.

The averaged spectra for three sets of groups (Figure 4) are determined:

1. The longest common length of the sections of the five groups seaward of the Gulf Stream. The very long Group 19 is divided into two sub groups. Set A represents conditions within the western region of the subtropical gyre.
2. The longest common length of the five groups. Again Group 19 is divided into two sub groups. The variation in Gulf Stream position and some slope water region is included in this set.
3. A long section composed of the two longest groups. This set is dominated by the subtropical gyre region.

The spectra characteristics show a nearly flat spectrum at wave lengths above 500 km, a nearly −2 power slope between 200 and 500 km wave lengths, a peak and trough near 100 and 200 km, respectively, with a flat spectrum at wavelengths below 100 km. The filter cut off at 10 km is clearly shown.

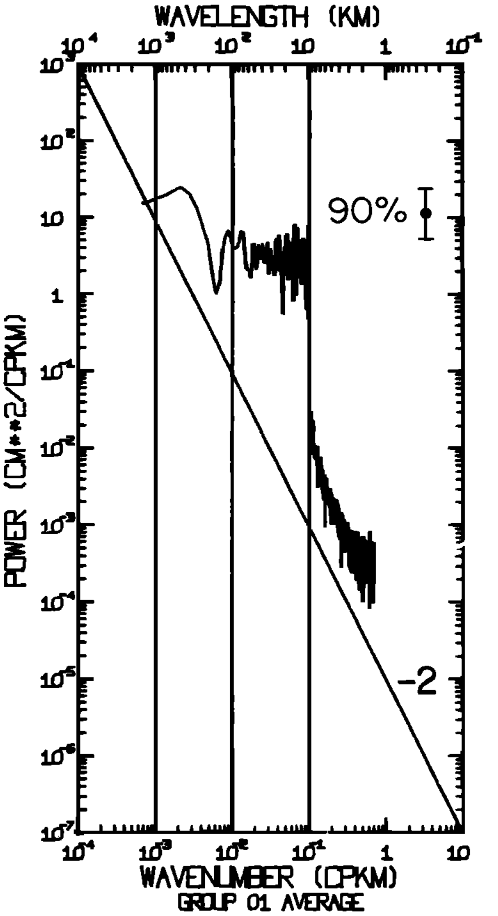

Fig. 3*b*. Spectra for Group 1 differences.

INTERPRETATION

The significance of the spectra (Figure 5) can be discussed in terms of available 'ground truth' data. The −2 slope from 200 to 500 km is similar to the spectra of isotherm topography found in the Pacific by *Bernstein and White* [1974]. This portion of the spectra is taken as representing real ocean signal. At lesser wave lengths the spectrum is nearly white, whereas the isopycnal structure observed by *Katz* [1973, 1975] suggests

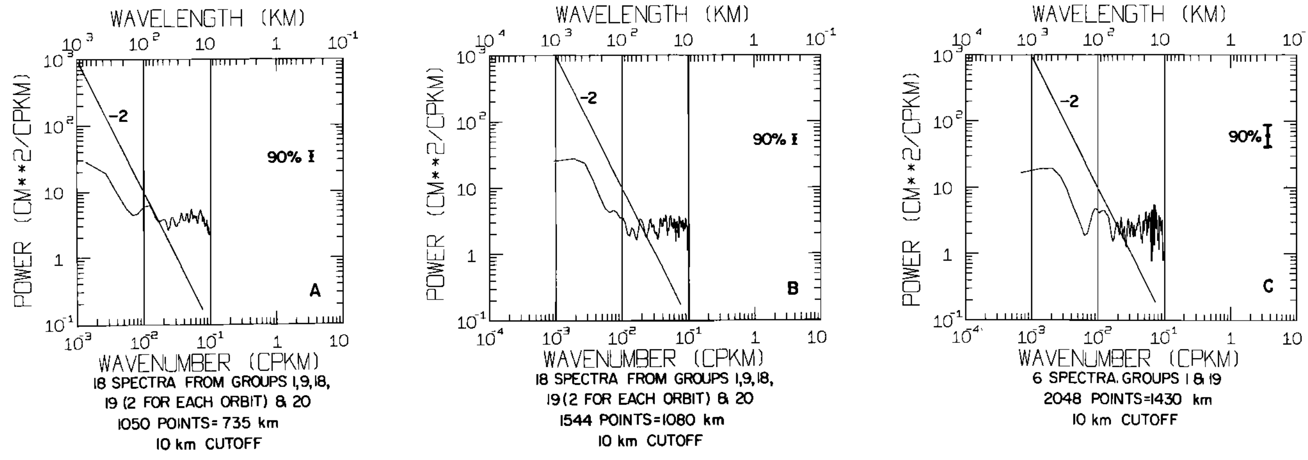

Fig. 4. Spectra for three sets of group. In sets A and B the long orbits of Group 19 are divided into 2 segments to increase statistical significance. Set A is entirely in the subtropical gyre. Set B crosses the Gulf Stream. Set C represents the longest significant grouping.

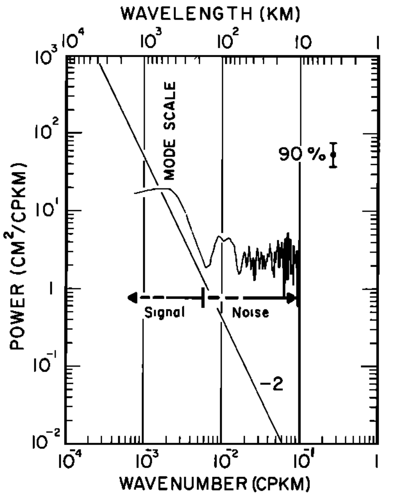

Fig. 5. Interpretation of set C spectra.

continuation at somewhat less than −2 slope into this region of the spectrum. Hence instrument noise is responsible for the white spectrum.

The peak at 100 km and trough at 200 km is probably noise, though the high frequency end of the *Bernstein and White* [1974] isotherm spectrum shows a similar structure. In addition, the width of the 100 km peak is surprisingly broad, even considering the logarithmic wavenumber scale. While noise seems to be the most likely explanation, further consideration may be warranted.

The flat spectrum above 500 km may not be entirely real, since the orbits may not be truly independent for the low frequency transients. The time separation of the orbits varies from 37 days to nearly 1 year (Table 1). Transient features with very long time scales may appear steady state to coincident orbits separated by shorter time. Assuming drift rates of transients of 1-5 cm/s (0.86–4.3 km/day), the time required for a lateral shift of a half wavelength of the transient feature is given in Figure 6 as function of transient spatial scale. Using 3 cm/s (about 2.5 km/day) as characteristic, half of the maximum sea level expression of a 200 km transient would be seen by coincident orbits of slightly less than 1 month separation, but a 500 km transient requires orbit separation of about 3 months and a 1000 km transient requires separation of slightly less than 6 months.

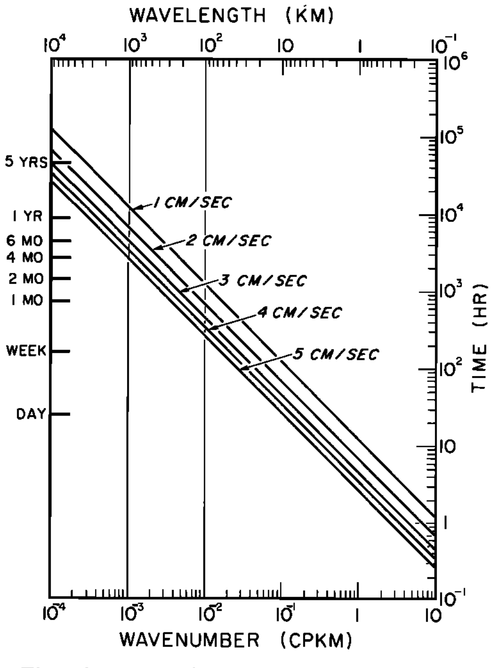

Fig. 6. Time (hours) required for one half wavelength translation of transients for 1-5 cm/s translation rates, as a function of transient wavelength.

Therefore detection of transients by coincident orbits depends not only on measurement precision of the altimeter and transient amplitude, but also on the time separation of orbits; it is possible that the drop off in energy above 500 km transients may be due to non-independent orbits for these larger transients rather than a real drop off in energy. However, set C (Figure 4), which is composed of two groups, each with at least one orbit pair separation of over 3.73 months, shows significant slope change near 500 km. Group one spectrum (Figure 3*b*), which has maximum separation in time of the five groups, displays the maximum drop off above 500 km. In addition, the 500 km peak is the same as observed for the Mode eddy scale. The slope change near 500 km is believed to be real, though the actual drop off may not be as large as indicated by the spectra.

CONCLUSION

It is concluded that the Geos 3 altimeter can reveal mesoscale transient features in energy spectra for wavelengths above 200 km. Mode scale transients are indicated.

The Geos 3 data may be used to investigate the spatial variation of sea level transients for the world ocean. The energy variations of the transients described for the subtropical gyre of the North Atlantic and North Pacific by *Bernstein and White* [1974, 1977], *Roden* [1977], and *Dantzler* [1976, 1977] may be tested and expanded for southern hemisphere subtropical gyres in addition to equatorial and more polar latitudes.

Preliminary inspection of the Seasat A altimeter reveals that it has much higher precision than does the Geos 3 altimeter. It is expected that Seasat A will allow for improved study of sea level transients.

We feel certain that satellite altimetry will become an important tool for physical oceanographers.

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