# NOTES AND CORRESPONDENCE

## On the Frictionless Influence of Planetary Atmospheric Waves on the Adriatic Sea Level

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ABSTRACT

The influence of planetary atmospheric waves on the Adriatic sea level is investigated for the year 1976 on the basis of 500 mb surface height and sea level data. Analysis is performed in time and frequency domains. It is found that—in the first approximation—the lower layers of the atmosphere are characterized by barotropic structure in the scope of the mentioned processes, while the equilibrium of sea-elevation gradient with air-pressure gradient is realized in the sea. Accordingly, sea level changes are opposite in phase to the oscillations of a selected isobaric surface; the ratio of their amplitudes is the same as the one between (sea surface) air density and density of the sea. Departures from this simple relationship result from the baroclinic atmospheric disturbances that occasionally influence the sea in the frequency band corresponding to planetary atmospheric waves.

### 1. Introduction

The influence of the atmosphere on sea level can be investigated from two points of view. On one hand, it is interesting to analyze the way *atmospheric factors* (air pressure, wind) act on the sea. On the other, it is of some importance to examine *atmospheric formations* that manifest themselves in the variability of sea-surface air pressure and wind and, therefore, contribute to the forced sea level changes.

For the Adriatic Sea area, the majority of papers follow the first approach. However, on several occasions the response of sea level to the influence of atmospheric formations has also been investigated. Special attention was paid to the synoptic meteorological scale in earlier analyses of this response. Kasumović (1958), Mosetti (1971) and Sguazzero *et al.* (1972) came to the conclusion that cyclones force the raising of sea level in the Adriatic, while anticyclones act in the opposite sense. Recently, studies have also been extended to the planetary scale disturbances. Penzar *et al.* (1980) analyzed sea level, air pressure and 500 mb surface height data in the time domain for Dubrovnik station for 1976. It was established that short-term oscillations of sea level (periods between tidal and ~10 days) are mainly the result of synoptic atmospheric disturbances, which confirmed the conclusions arrived at by other investigators. For long-term oscillations of sea level (periods of ~10 days and more) it was shown that they are predominantly caused by the passage of planetary atmospheric waves above the Adriatic Sea.

The last conclusion cited represents the starting point of this investigation. The objective of the study is to achieve a more detailed understanding of the influence of planetary atmospheric waves on the Adriatic sea level. With this aim in view, previously performed comparisons of the geopotentials of 500 mb surfaces with sea level will be expanded, by considering a greater number of data and performing the analyses both in time and frequency domains. This should serve as a basis for the development of adequate conceptual models, which will be used to illustrate the basic mechanisms of interactions in the atmosphere–sea system.

### 2. Geopotentials of 500 mb surface

Geopotentials of the 500 mb surface were obtained from the charts issued daily (Deutscher Wetterdienst, 1976). For 0000 GMT and for every day during the year 1976, values of geopotential were read at four positions above the Adriatic Sea, along the meridian 15°E (points G1–G4, Fig. 1). Mean values of the simultaneous values were then determined, enabling oscillations of geopotential, connected with the planetary-scale disturbances, to be clearly recognized. This procedure led to the time series of the mean geopotential of 500 mb surface, expressed in geopotential meters and shown in Fig. 2.

The curve shows a pronounced oscillation with a period of one year, having a minimum in winter and maximum in summer; it may be explained by thermal influence. Numerous oscillations of shorter periods are superimposed on the basic oscillation. In order to explain their origin, one should take into account the results of the investigation of atmospheric processes demonstrated by Palmén and Newton (1969) among others.

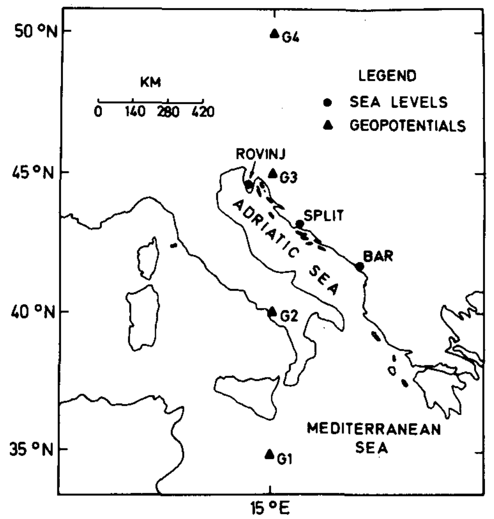


FIG. 1. Map of the Adriatic Sea region showing locations of sea level and geopotential sampling points.

Among various atmospheric occurrences, planetary atmospheric waves are of a special importance. These waves manifest themselves in the wavy shape of isobaric surfaces as well as in the wavy shape of streamlines. Principally, a series of 4 or 5 such waves encompasses each hemisphere, which means that wave lengths fall in the interval 6000–8000 km. The amplitude of the waves may extend over $\sim 40°$ latitude, and the entire system (or some parts) travels mainly eastward, relatively slowly at an average speed of $\sim 1$–8 m s$^{-1}$. One important property of planetary atmospheric waves in the troposphere is that their structure shows small variations along the vertical, the shape of streamlines and isobaric surfaces being similar at all levels (Eliasen and Machenhauer, 1969). That emphasizes the possibility of the sea being influenced by planetary atmospheric waves, suggesting at the same time the comparison of geopotentials of an isobaric surface (e.g., 500 mb) with sea levels as a powerful tool in the analysis of the atmosphere–sea interaction.

Here, the question may be put forward—why bother about the connection between geopotentials and sea levels instead of simply investigating the relationship between sea-surface air pressure and sea level height? The answer is that this approach enables various baroclinic atmospheric disturbances that cause the variability of meteorological parameters at the sea surface and not in the upper layers of the troposphere, to be excluded from the analysis. Therefore, only barotropic phenomena remain, among which planetary atmospheric waves are the most important.

From the previously stated dimensions and speeds of planetary atmospheric waves it may be concluded that they generate the variations of geopotential at periods of $\sim 10$ or more days. Figure 2 also shows that oscillations of smaller periods exist. Consequently, these oscillations are due to the faster and smaller baric formations connected with the cyclonic and anticyclonic occurrences in the atmosphere. The range of periods of these formations overlaps to a certain extent with the interval of periods of planetary atmospheric waves. However, the greater part of such disturbances occurs at periods less than 10 days, indicating (along with the above mentioned seasonal oscillation) that the investigation of planetary atmospheric waves and their influence on sea level may be effectively carried out by concentrating on one frequency band.

## 3. Sea levels

In addition to the 500 mb surface height data, daily means of sea level were also used (Hydrographic Institute of the Yugoslav Navy, 1977) for 1976 at stations Rovinj, Split and Bar (Fig. 1). Such sea levels

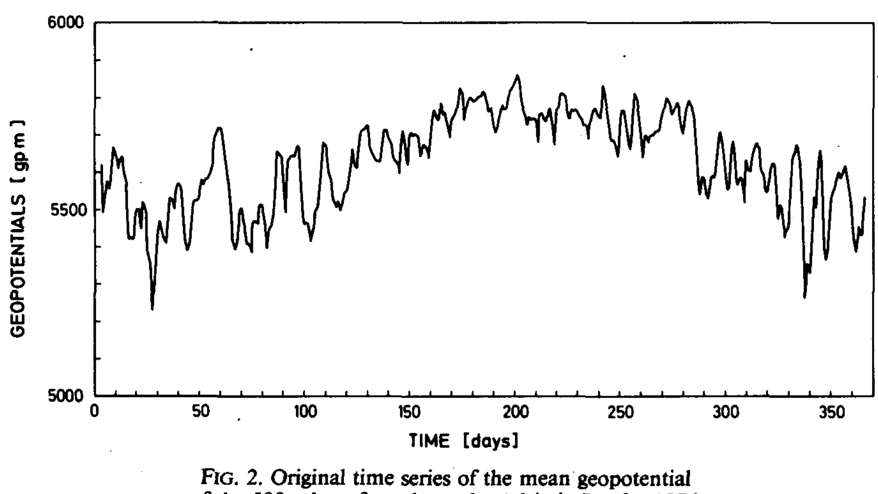


FIG. 2. Original time series of the mean geopotential of the 500 mb surface above the Adriatic Sea for 1976.

represent 24 hour mean values (0000–2300 EMT), expressed in centimeters, and are related to the local tide-gage zero. Application of the daily moving average may be regarded as a relatively effective way of eliminating the oscillations of tidal periods for the Adriatic Sea area. As an illustration, absolute values of the amplitude of the $M_2$ tidal component after filtration are as low as 0.68 cm (Rovinj), 0.28 cm (Split), and 0.32 cm (Bar). Accordingly, no problems with aliasing, caused by sampling at 24 h intervals, are to be expected.

Time series of mean sea level are presented in Fig. 3. On all of the curves there is a pronounced basic oscillation with a period of one year, having a minimum in spring and maximum in autumn. That oscillation may be connected with the variations of density, which in turn originate from the influence of mechanical or nonmechanical factors. These processes are of baroclinic nature and they include variations in the current field. Some authors emphasize the importance of barotropic phenomena related to the occurrence of seasonal oscillation in sea level; sometimes the influence of the changes of sea water mass in the oceans and seas is also stressed in this context. Investigations of the seasonal oscillation of the Adriatic sea level, performed to date (Zore, 1960), were aimed at the explanation of the relationship of sea level to the distribution of water masses and currents in the sea.

On the basic sea level oscillation, numerous variations of smaller periods are superimposed (Fig. 3). According to the opinions put forward up to now, the main cause of these variations is the atmosphere, i.e., those factors influencing the sea—air pressure and wind. As far as atmospheric formations are concerned, at periods $\geqslant 10$ days the dominant influence of planetary atmospheric waves is expected, while at shorter periods the action of cyclonic and anticyclonic disturbances is of main importance. In the following, we shall concentrate on the first of these influences.

## 4. Relation of sea level fluctuations to atmospheric forcing

The mutual relationship between geopotentials of the 500 mb surface and sea level will be investigated here to determine the nature of the influence of planetary atmospheric waves on the sea. Analyses will be performed in the time and frequency domains. Methods were selected on the basis of previous knowledge of the atmosphere–sea interaction and especially of the processes worked out in detail in this paper. Characteristics of the data base—e.g., the fact that the data were given in the form of time series and that discrete values were on disposal—were also important in choosing the methods.

From time series of geopotentials and sea levels, the basic annual oscillations were eliminated first. To achieve that goal, a cosine function of angular frequency $2\pi/365$ (day$^{-1}$) was fitted to the data by applying the least-squares method. Next, approximated values were subtracted from the original data. The time series thus obtained were low-pass filtered by use

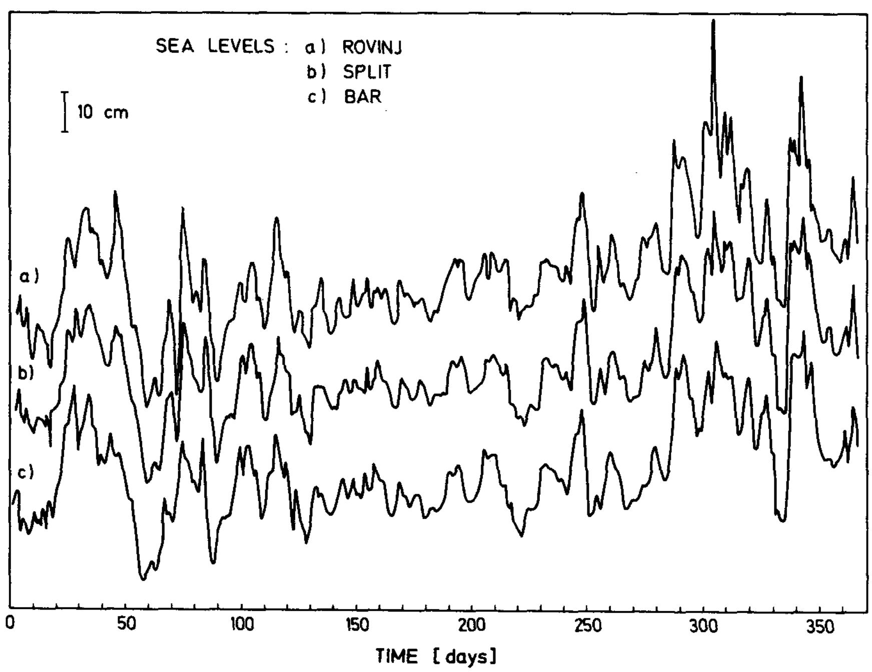


FIG. 3. Daily means of sea level at three stations in the Adriatic Sea in 1976.

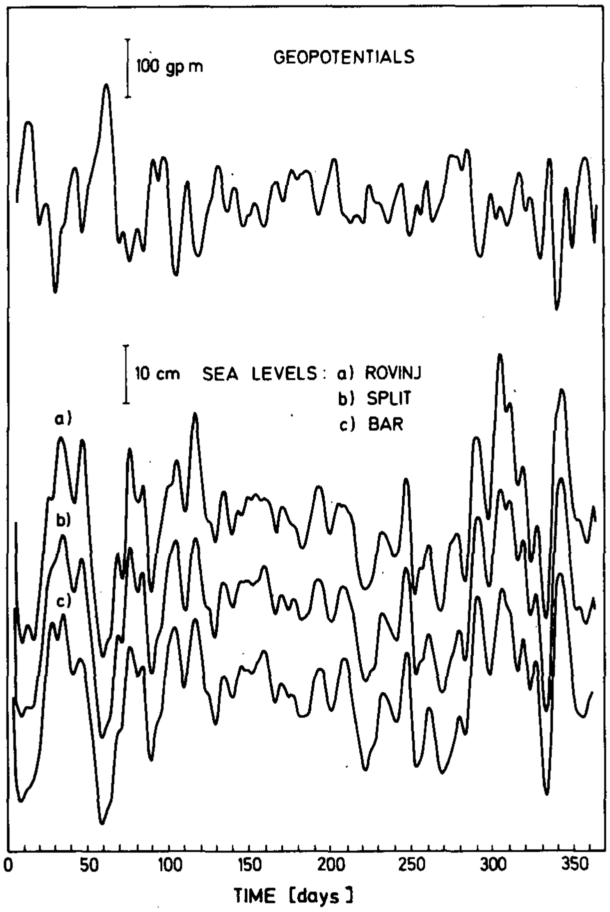


FIG. 4. Band-pass filtered (cutoff frequencies 0.1 and 0.01 cpd) time series of geopotential and sea level for the Adriatic Sea area and the year 1976.

of a moving average with binomial weights. A filter was selected that comprises nine successive terms of the analyzed data series, implying that it cuts off the oscillations with periods ≤10 days, while allowing the fluctuations of greater periods to pass.

These time series are presented in Fig. 4. On the upper part of the figure geopotentials are drawn, while the lower part shows simultaneous values of sea level for stations Rovinj, Split and Bar. The first thing that may be noticed is that sea levels at various stations follow almost the same course in time. We conclude that in the frequency band analyzed the Adriatic Sea reacts to the influence of external forces as a whole, which might be expected since filtration isolated the disturbances characterized by great temporal and therefore great spatial dimensions. The next thing that may be observed in Fig. 4 is that, in the first approximation, every pronounced oscillation on the lower curves of the sea level corresponds to the opposite oscillation on the upper geopotential curve: i.e., as the 500 mb surface above the Adriatic rises the sea surface is depressed, and vice versa. Also, amplitudes of the oscillations of geopotential in the figure are only slightly smaller than amplitudes of the sea level oscillations, which—along with the fact that ordinates are chosen in such a way that the interval of 100 gpm on the geopotential scale corresponds to a 10 cm interval on the sea level scale—leads to the conclusion that the ratio of the geopotential to the sea level variations is approximately 1000:1. Such a relationship reminds one of the ratio of sea density to air density. Therefore, we can conclude that oscillations of geopotential are approximately as many times greater than the sea level oscillations as sea-surface air density is smaller than the density of the sea. This would be expected under isostatic conditions.

The range of geopotentials, in the frequency band considered here, amounted to ~400 gpm in 1976. The corresponding range of sea levels amounted to some 50 cm, which may be regarded as a significant amount both for the Adriatic and the Mediterranean Seas.

If we turn our attention once more to Fig. 4, we shall see that the marked departures from the simple relationship of geopotentials and sea levels just described occurred on three occasions. In the first ten

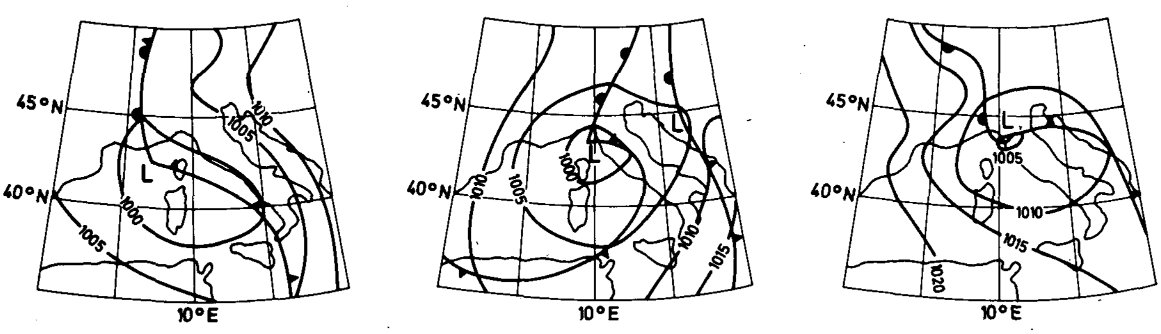


FIG. 5. Surface synoptic charts illustrating the presence of cyclonic disturbances above the Adriatic Sea area. Over the period 24 October–14 November 1976 the Adriatic sea level rose much more than expected from the variations of geopotential. This was due to the low pressure and the southern winds which, in turn, were connected with synoptic atmospheric disturbances and forced a storm surge along the east coast of the Adriatic Sea.

days of August the sea level sank much more than would be expected from the variations of geopotential. Occurrences of fall, rise and repeated fall of sea level unconnected with geopotential oscillations were recorded between 6–23 September, while over the period 24 October–14 November the Adriatic sea level rose much more than it should—according to the geopotential curve. As follows from the analysis of synoptic situations (Deutscher Wetterdienst, 1976) (e.g., Fig. 5) all the mentioned occurrences may be ascribed to the closed baric systems in the lower, middle and upper troposphere that act on the Adriatic sea level through the air pressure and especially through the strong and widespread air flow of favorable direction and duration. These baric systems do not significantly influence the mean geopotential of the 500 mb surface above the Adriatic Sea, bringing about the departures of the sea level variations from the inverse variations of geopotential.

Therefore, it may be concluded that planetary atmospheric waves influence the sea level height through changes of air pressure above the sea. The atmosphere is characterized by barotropic structure in the scope of these processes, while the response of the sea may well be described by equilibrium theory, i.e., theory based on the equilibrium between air-pressure gradient and sea-elevation gradient. In the frequency range corresponding to planetary atmospheric waves other baric formations may influence the sea surface through the air pressure and through the wind. Thus, sea level oscillations can depart significantly from the fluctuations expected by observing solely the movements of planetary atmospheric waves over the sea.

The relationship of geopotentials and sea levels was analyzed not only in the time domain, but in the frequency domain as well. Coherence-squared spectra, phase-lead spectra, and gain-factor spectra were determined for stations Rovinj, Split and Bar (Figs. 6a–c). The linear trend was eliminated from the original time series by least-squares fitting to a straight line, and a cosine-taper function was applied. Complex spectra were determined via the FFT method, and power-spectral density functions and cross-spectral density functions were obtained. These last spectra were smoothed by taking the mean of ten successive values along the frequency axis. Finally, coherence-squared spectra, phase-lead spectra and gain-factor spectra were obtained, as well as the limiting value of the coherence-squared function at the 90% significance level.

Figs. 6a–c show great similarity. At all of the stations coherence squared is significantly high for frequencies 0.1–0.01 cpd—i.e., for the frequency band in the atmosphere dominated by planetary waves. We conclude that in this span of frequencies the atmosphere–sea system, connecting geopotentials and sea

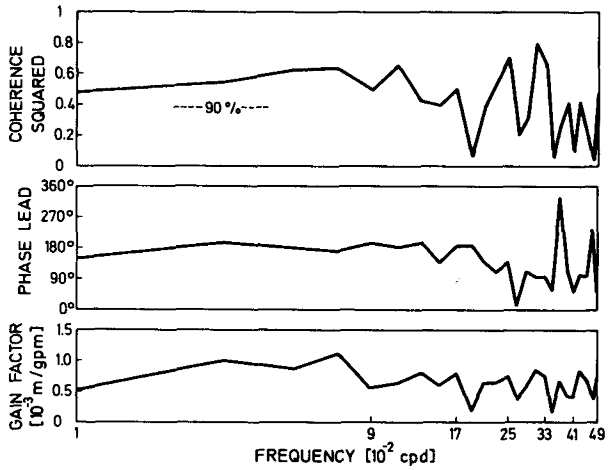


FIG. 6b. As in Fig. 6a except for station Split.

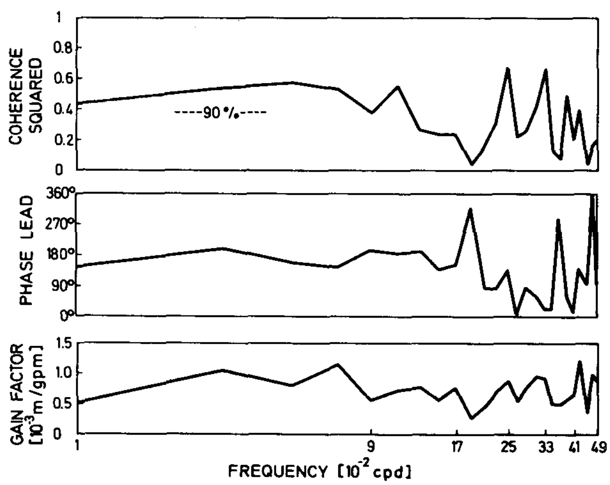


FIG. 6a. Coherence-squared, phase-lead and gain-factor spectra for geopotentials and sea levels at station Rovinj for the year 1976.

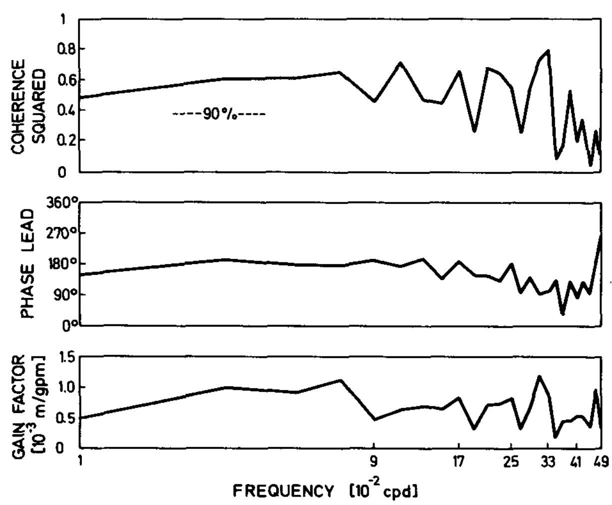


FIG. 6c. As in Fig. 6a except for station Bar.

levels, may well be approximated by a constant-parameter linear system with a single input and a single output. In the same frequency band, the phase lead of geopotentials relative to sea levels varies ~180°, indicating that the relationship of the two series is approximately linear and that the proportionality coefficient is negative. Finally, the gain factor for all the figures is close to $1 \times 10^{-3}$ m gpm$^{-1}$ for frequencies corresponding to the planetary atmospheric waves. This points to the sea level oscillations being ~1000 times smaller than the variations of geopotential.

The conclusion is similar to the one drawn in the time domain; namely, that the passage of planetary atmospheric waves over the sea brings about the variations in sea level, through air pressure changes, and that the characteristics of the atmosphere–sea system can be described in the following simplified way:

atmosphere—barotropic structure

sea—equilibrium state.

The fact that coherence squared is smaller than unity and that the phase lead and gain factor show variations around the amounts cited indicates that the foregoing result may be regarded as a first approximation of the processes in nature on the planetary scale.

## 5. Discussion

The analysis of observations opens the question of physical mechanisms regulating the existence of planetary atmospheric waves and controlling the influence of these waves on the sea—especially on the Adriatic sea level. Understanding relevant mechanisms makes the preparation of simple conceptual models possible, and these may represent the basis for more complex simulations.

If the atmosphere–sea system is examined, the simplest approach is to analyze two layers representing the atmosphere and the sea and to assume that they are decoupled. Intuitively, such a presumption may be justified by taking into account the fact that air density is much less than sea-water density. Evidently, amplitudes of motions in the atmosphere will thus be much greater than amplitudes of forced sea motions (except in the case of resonance), enabling occurrences in the atmosphere to be analyzed separately from their influence on the sea. Therefore, planetary atmospheric waves will be satisfactorily described by the usual "meteorological" models, the simplest of which (Rossby *et al.*, 1939) demonstrates that the ideal homogeneous atmosphere in purely horizontal motion allows the existence of wave disturbances due to the variation of the Coriolis parameter with latitude.

It should be pointed out that the geostrophic balance of forces is the main feature in forcing caused by the passage of the planetary wave through the atmosphere above the sea. Therefore, for the unbounded inviscid sea, the state of the so-called frozen surface (Brown *et al.*, 1975) may be expected under the usual circumstances. There are two mechanisms able to perturb the geostrophy in inland seas, bringing about the atmospherically forced motions that follow the equilibrium law. One is connected with the channelizing effects, as was shown by Proudman (1929). The other originates from the influence of bottom friction and was clearly demonstrated by Miyazaki (1952) and Crépon (1976) for shallow seas and great periods of atmospheric disturbances. Which of the mechanisms mentioned is the dominant one for the Adriatic Sea area? Future investigations should provide an answer to this question.

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