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The variations of temperature, pressure and wind speed values: Effects on gravity waves(*)

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Summary. — According to the theoretical studies, gravity waves, which are excited in the lower atmosphere, can transport momentum and energy on to the upper levels. Gravity waves are attenuated by interacting with the large-scale wind motions in the upper part of the middle atmosphere. Different meteorological parameters and atmospheric circulations are known as one of the sources of excitement of gravity waves. The main purpose of this paper is to analyze the onset of some gravity waves (GWs), and seasonal variations of gravity waves over Istanbul. Radiosonda data of Istanbul in troposphere and lower stratosphere (1000 hPa–30 hPa) between 1993 and 1997 is analyzed. Daily, monthly and annual variation of pressure heights, air temperature, horizontal wind speed and deviations from mean values are interpreted. Zonal and meridional wind speed variations show the effects of gravity waves for different pressure levels in the troposphere. These waves lead the meso-scale wave-form structures in spring, autumn and winter.

PACS 92.60.-e – Meteorology.
PACS 92.60.Dj – Gravity waves, tides, and compressional waves.
PACS 92.60.Gn – Winds and their effects.

1. – Introduction

Radiosonde data suggest the formation of gravity waves at a speed equal to that of the background wind, at some levels of the troposphere [1]. The role of gravity waves on the development of cumulus clouds is studied [2]. In some special cases a harmony is observed between gravity waves, convection and some meso-scale waves in and near vicinity of cumulus clouds [3]. Gravity waves (GWs) influence local meteorology

(*) The authors of this paper have agreed to not receive the proofs for correction.

and large-scale atmospheric circulation. Main tropospheric sources of gravity waves are known as topography, convection, pressure systems, fronts and wind shear. Atmospheric gravity waves can only exist in the stable stratified atmosphere. A fluid parcel displaced vertically will undergo buoyancy oscillations. The buoyancy force is the restoring force responsible for gravity waves [4]. Gravity waves (buoyancy waves) can transport and redistribute momentum and energy. They can strongly influence the moisture field.

Two-dimensional numerical simulations are performed to investigate the nature of tropospheric internal gravity waves of the type which are observed to occur above active thermal convection over an unstable boundary layer [5]. These gravity waves are cited by a combination of pure thermal forcing, the boundary layer eddies and cumulus clouds acting as obstacles to the flow in the presence of mean environmental wind shear. Widespread gravity wave systems have been found to exist over convectively active boundary layers in the presence of vertical wind shear [6].

The temperature inversions that produce superior mirages are capable of supporting gravity (buoyancy) waves of very low frequency and long wavelength. Lehn *et al.* described the optics of single mode gravity waves that propagate in a four-layer atmosphere [7]. The interaction between internal waves (IW) and wind waves (WW) is studied [8]. Attenuation of IWs propagating against wind is the strongest. A global spectral model extending approximately from 15 up to 120 km is used in both diagnostics and simulations of the observed monthly middle atmospheric climatology as represented in the CIRA-86 empirical model [9]. The simulation results obtained using the diagnosed zonal forcing and vertical diffusion coefficient compare favorably with the empirical model and with simulations using a gravity wave parameterization.

A two-dimensional cloud-resolving model is used to examine the possible role of gravity waves generated by a simulated tropical squall line in forcing the quasi-biennial oscillation of the zonal winds in the equatorial stratosphere [10]. In the easterly and westerly shear cases, westward and eastward propagating waves, respectively, are strongly damped as they approach their critical levels, owing to the strongly scale-dependent vertical diffusion in the model. The magnitude of the zonal forcing is of order $5\ \mathrm{m/s \cdot day}$.

Profiles of wind velocity and temperature at 0–35 km are observed by means of radiosondes in west Java, Indonesia, during November 1992 and April 1993 [11]. They study the behavior of various atmospheric waves in the equatorial atmosphere. An oscillation of zonal winds with 27 days was found in the troposphere, which was associated with variations in humidity and cloud top height.

Another paper proves that large spatial-scale gravity waves with amplitudes and periods of the pressure perturbations the same as the reduced system component of the solution can be generated by meso-scale storms [12].

Lott presents observations and parameterization of sub-grid scale orography (mountain gravity waves) in large-scale atmospheric models [13]. The different scales of atmospheric response to topographic forcing, gravity and lee waves are presented in this study [14].

In the present study, annual, seasonal, monthly and daily variations of pressure height, temperature, horizontal wind speed, wind components and gravity waves are statistically analyzed by using radiosonda data in Istanbul. The results are in good agreement with the analysis presented in the previous study using some observation of meteorological parameters of the troposphere and the lower atmosphere [15,16].

2. – Material and method

2˙1. *Material.* – The data from radiosonda station in Göztepe (40°55′N, 29°05′C) at 00:00 GMT for different pressure levels (1000, 850, 700, 500, 300 and 30 hPa) observed between 1993 and 1997 are processed. Each radiosounding gives a high-resolution profile of temperature, altitude and horizontal wind velocity.

Daily average deviations of geo-potential heights above from mean sea level and time variation of air temperature turbulence, zonal and meridional wind component values are examined.

2˙2. *Method.* – Turbulent motions and internal gravity waves are induced by surface irregularities. Terrain-generated gravity waves are common in the stable PBL and these waves can generate much Reynolds stress and surface drags due to turbulent motions. Turbulent structure of pressure height, air temperature and wind velocity have been analyzed in this paper [15].

2˙2.1. Fundamental equations. For gravity waves, the main restoring force is gravity as distinct to acoustic gravity waves caused by the pressure gradient [17]. The basic equations for gravity waves, by assuming

i) Two dimensions (ignore motion or gradients along the y direction).

ii) The horizontal scale of the wave is sufficiently small that the Coriolis term may be neglected by comparison with the other terms.

iii) Ignore the friction term.

iv) The unperturbed atmosphere is at rest.

The components of the momentum equation are

$$\frac{\mathrm{d}u}{\mathrm{d}t} + \frac{1}{\rho}\frac{\partial P}{\partial x} = 0\,, \tag{1}$$

$$\frac{\mathrm{d}w}{\mathrm{d}t} + \frac{1}{\rho}\frac{\partial P}{\partial z} + g = 0\,. \tag{2}$$

The continuity equation becomes

$$\frac{1}{\rho}\frac{\mathrm{d}\rho}{\mathrm{d}t} + \frac{\partial u}{\partial x} + \frac{\partial w}{\mathrm{d}z} = 0\,. \tag{3}$$

Let perturbations be introduced in these equations, such that

$$u = u', \quad w = w', \quad \rho = \rho_{\mathrm{av}} + \rho', \quad P = P_{\mathrm{av}} + P' \quad \text{and} \quad V = V_{\mathrm{av}} + V'\,, \tag{4}$$

where u and w show wind speed components. t and ρ are time and air density.

P, T and V denote the pressure, temperature and the horizontal wind speed, respectively; g is the acceleration of gravity acting in negative z direction. Subscript "av" indicates an average over a characteristic time or horizontal spatial scale. The fluxes, in turn, will depend on ρ', V', T' and P' which, in the case of gravity waves, will be related to each other by well-defined expression.

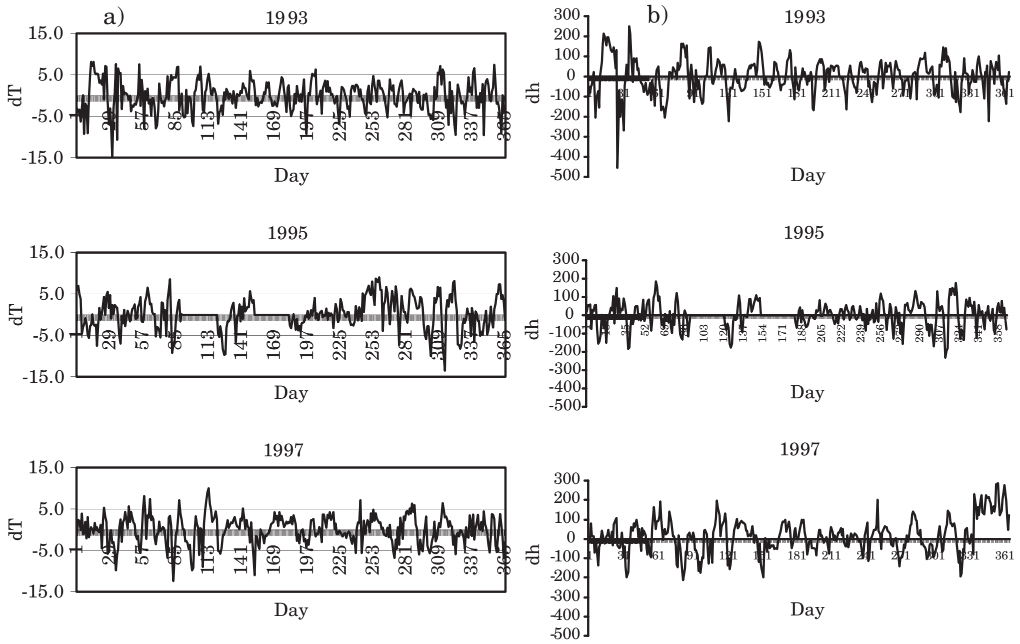

Fig. 1. – (a) Daily variation of dT values in 500 hPa pressure level in 1993, 1995 and 1997. (b) Daily variation of dh values in 500 hPa pressure level in 1993, 1995 and 1997.

3. – Analysis and results

3˙1. *Seasonal variation.* – Daily variations of dT and dh values of 500 hPa pressure level are given in figs. 1 (a) and (b), respectively. Table I shows mean seasonal deviation values of pressure heights (dh) and temperature (dT) at the lower atmosphere between 1993 and 1997. Annual mean deviation (dh) values in upper levels are greater than dh values in lower pressure levels (133.6 gpm at 300 hPa, and 35 gpm at 1000 hPa). In general, the greater deviation values are observed in winter (January and February) and spring and minimum values are observed in summer (in July and August). dh values observed in 1993 and 1997 are greater than the values observed especially in the lower troposphere between 1994 and 1996. The greater annual deviations of dT values are observed at 850 hPa pressure level between 1993 and 1997. Generally the higher dT values are observed in spring and autumn, the lower ones are observed in summer (July ad August). dT values observed in 1993 and 1997 are greater than the values especially observed at the lower troposphere (between 1000 and 700 hPa pressure levels) between 1994 and 1996. 1997 is the warmest period.

Table II shows a linear relation and correlation coefficients (r) between dT and dh (deviations of temperature and pressure height values). The higher correlation coefficients ($0.63 < r_{\max} < 0.77$) are defined between dT and dh values at 500 hPa and 700 hPa. By considering two confidence levels ($\alpha = 0.1$ and $\alpha = 0.5$; $n = 365$, d$f = 363$), confidence intervals are defined as 99% and 95%, respectively. Absolute values of the test statistic do exceed the critical value. That is the test statistic does fall within the critical region. There is sufficient evidence to support the claim of the linear relation between two parameters.

TABLE I. – *Seasonal and annual variations of* dh *and* dT *values between 1993 and 1997 in different pressure levels.*

	dh					dT				
300 hPa	Spring	Summer	Autumn	Winter	Annual	Spring	Summer	Autumn	Winter	Annual
1993	125.86	95.04	115.76	15.37	124.30	5.69	3.54	2.93	3.07	4.07
1994	120.76	79.67	64.57	105.08	99.72	3.04	2.87	4.77	2.07	3.36
1995	130.42	58.27	136.63	172.43	78.49	3.16	2.33	3.14	2.91	2.75
1996	119.6	76.32	121.79	169.92	105.13	2.76	3.49	3.70	3.17	3.20
1997	129.79	84.60	106.32	90.82	133.62	3.08	3.06	2.82	2.15	3.06
500 hPa										
1993	87.81	57.75	70.05	79.27	84.76	3.38	2.76	3.23	3.34	3.59
1994	80.05	53.15	42.37	73.13	66.93	3.34	2.08	1.96	3.18	2.68
1995	80.76	35.37	85.48	66.22	70.78	4.18	1.78	4.92	4.80	3.91
1996	79.73	51.75	76.73	66.54	69.62	3.44	3.07	3.44	3.08	3.76
1997	91.69	51.88	72.72	55.51	87.11	4.20	2.73	3.15	3.06	3.36
700 hPa										
1993	60.26	32.57	45.06	54.63	58.99	3.58	3.46	4.32	3.63	4.24
1994	54.03	40.10	28.46	54.09	47.60	3.87	2.79	2.65	4.00	3.24
1995	47.19	25.54	49.91	46.93	45.10	4.45	1.98	4.58	3.80	3.91
1996	54.20	33.41	50.40	44.8	47.53	4.25	3.12	3.65	4.00	3.85
1997	56.87	53.84	46.90	41.63	51.69	4.76	3.15	3.40	3.52	3.91
850 hPa										
1993	48.93	25.77	32.42	46.16	42.38	4.66	3.98	5.71	3.83	4.91
1994	38.56	30.20	37.31	50.58	40.09	5.28	3.30	3.60	4.64	4.20
1995	36.89	23.70	41.83	50.52	40.60	4.96	2.07	4.52	4.57	4.26
1996	44.22	25.31	39.61	43.88	40.81	4.41	3.58	3.77	4.72	4.05
1997	47.11	28.5	38.70	48.65	39.72	4.70	4.55	4.37	4.86	4.61
1000 hPa										
1993	40.28	29.72	43.53	44.78	43.10	4.16	2.33	3.99	3.62	3.55
1994	35.62	27.65	30.44	56.37	34.86	4.43	1.99	2.39	4.09	3.31
1995	38.13	26.11	42.27	61.21	44.75	3.73	1.14	3.06	3.91	3.24
1996	38.93	28.20	39.46	53.90	42.47	2.90	1.96	3.14	3.86	3.09
1997	49.37	30.68	43.39	67.25	45.99	4.39	2.62	3.05	4.03	3.62

TABLE II. – *Linear relation between* dh *and* dT.

r	1993	1994	1995	1996	1997
1000	0.34	0.21	0.51	0.11	0.37
850	0.07	0.23	0.11	0.07	0.05
700	0.50	0.63	0.50	0.17	0.47
500	0.75	0.77	0.64	0.64	0.66

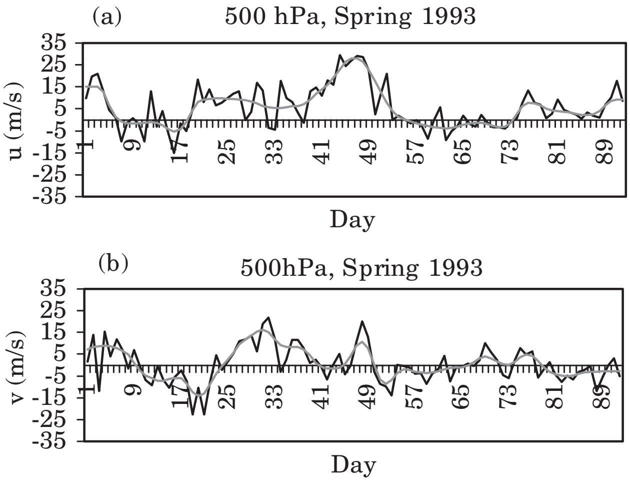

Fig. 2. – (a) Zonal wind speed (raw and smoothed data), (b) meridional wind speed (raw and smoothed data); 500 hPa, Spring 1993.

3˙2. *Daily variation*

3˙2.1. Zonal and meridional wind speed. Daily variations of two wind speed components (u: meridional; v: zonal) in 1000 hPa, 850 hPa, 700 hPa, 500 hPa and 300 hPa pressure levels are analyzed. Figures 2 (a) and (b) show the daily variation of zonal (u) and meridional (v) wind speed values at 500 hPa pressure level in spring, 1993. Results of analysis of wind speed values for different seasons between 1993 and 1997 are summarized as follows:

1) Generally u components have positive values in 700 and 500 hPa pressure levels in spring. It means that zonal winds are westerly during this period [15]. These results are in good agreement with the results on time variations of gravity waves.

2) Temperature distribution displays that there is more stable stratification in summer than the other seasons. In this period, a fluid parcel can displace vertically and will undergo buoyancy oscillations. Gravity waves directly affect on the physical processes occurring within the layer and in addition, they may be a major link between atmospheric boundary layer and the atmosphere above [17]. In spring, autumn and winter, gravity waves are associated with convective structure, synoptic situation and planetary waves. In summer from the lower troposphere to 500 hPa pressure level, wave frequency shows increasing trend, and amplitude values show decreasing trend. Wave period changes between 15–17 days [15]. Wave frequency shows an increasing trend from lower to 700 hPa in spring. Wave period changes in the range between 11 and 13 days.

3) Amplitude values of u and v wind speed components show an increasing trend from the lower troposphere (1000 hPa) to upper (300 hPa) layers. Deviation values observed in May are also smaller than the values observed in March and April except 300 hPa pressure level. Amplitudes of meridional wind speed are larger in winter, spring and autumn. They decrease in summer. (As mentioned above, in spring, autumn and

winter, gravity waves are associated with convective structure, synoptic situation and planetary waves.)

4) Oscillation numbers of u and v; zonal and meridional wind speed values are different. Wavelength of meridional wind speed values (11–13 days) is larger than wavelength of zonal wind speed values (8–9 days) in spring, 1993.

5) Hence the probability of gravity waves at the lower troposphere (especially, 1000 hPa and 500 hPa pressure levels) is higher than the other seasons in spring. As a case study data observed in spring, 1993 is presented in this study.

4. – Conclusion

Characteristics of atmospheric waves in lower layer atmosphere (in the troposphere) are analyzed by using radiosonda data of Istanbul between 1993 and 1997.

In order to examine the efficiency of the gravity waves, we have established a relation between temperature, turbulence parameters and geo-potential height values at 1000, 500, 30 hPa pressure levels. Linear correlation coefficients between geopotantial height values and temperature turbulence parameters show the existence of gravity waves.

The higher correlation coefficient is defined at 500 hPa. It becomes very difficult to examine the gravity waves in the lower atmosphere because of the very complicated dynamic and thermal structure in which friction forces and surface effects in the boundary layer ($h < 1.5$ km) become important. On the other hand, the correlation coefficient between geo-potential height and temperature turbulence parameter shows the existence of gravity waves and their maximum value at 500 hPa (at 5656 km) pressure level. This result shows that gravity waves have an important role associated with convective structure, synoptic situation and planetary waves at this level of the atmosphere.

In this present study, by considering daily variations of temperature, the time variations of large-scale gravity waves have been analyzed. It is concluded that correlation coefficient at 500 hPa was higher than 1000 hPa and 300 hPa pressure levels. The lower values of correlation coefficient are observed in mixing layer (at 1000 hPa and 850 hPa pressure levels). This can be explained by the thermodynamically, complicated physical processes and different effects, which play an important role on pressure fluctuations. The amplitude of temperature oscillations is higher in lower levels (especially at 850 and 700 hPa pressure levels). The amplitudes of the pressure oscillations are higher in upper levels [15].

The impact of the sampling frequency of the assimilated data on the global atmospheric circulation and aliasing of the semidiurnal cycle has been investigated in the earlier studies [18]. The Northern Hemisphere (NH) lower troposphere is characterized by two major oceanic lows and three continental highs. Since the spatial structure of the lower tropospheric circulation differs considerably from the upper tropospheric one, variations of pressure height deviations at 850 hPa and 300 hPa levels (not shown) definitely differ from each other. The lower troposphere (1000–850 hPa) consists of three oceanic anticyclones over the Pacific, Atlantic, and Indian Oceans and major land lows over the Eurasian continent and the Mexican monsoon region during boreal summer in the NH. In the boreal winter, distinctive differences exist between the upper and lower tropospheric circulations. The east-west circulation, velocity potential became a conventional variable in depicting the global divergent circulation. As a conclusion

1) Pressure oscillations are described as big gravity waves. Amplitudes of annual pressure oscillation during the observation period are greater in the upper troposphere.

2) Temperature deviations ($\mathrm{d}T$) are smaller at the lower troposphere.

3) Generally, the higher positive perturbations ($V > V_{\mathrm{av}}$) are observed between 500 and 300 hPa.

4) The east-west circulation, velocity potential became a conventional variable in depicting the global divergent circulation [18]. The results of the present paper show that amplitudes of u component (zonal wind) at 500 and 300 hPa were greater than the values observed at 1000 and 850 hPa pressure levels. In summer season, wave amplitudes decrease at all levels.

5) Average wave period changes between 8 days (minimum value) and 13 days (maximum value) in spring by analyzing the daily variation of zonal and meridional wind components.

6) Gravity waves are generated in the troposphere and propagated upward into the stratosphere. In general, the harmony of gravity waves with convective structure causes to form cumulus congestus clouds and to observe cumulus waves, in the atmospheric boundary layer. In order to examine small-scale gravity waves, one should analyze temperature variations, which are based on a more sensitive and fast measuring system.

7) The hourly data over a long time period is an effective way to eliminate transient atmospheric disturbances. Thus, the long-term averaged hourly data contain only the climatological value and the diurnal and semidiurnal components of any meteorological variable. The importance of aliasings in these semidiurnal modes is determined by their impacts on the depiction of atmospheric general circulation.

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