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AN ANALYSIS OF VERTICAL PROFILES OF WIND AND HUMIDITY BASED ON LONG-TERM RADIOSONDE DATA IN TURKEY

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ABSTRACT

The prediction of atmospheric variables is fundamentally important for flight, and efficiency with environmental impact analyses of aircraft. However, certain variables are less predictable leading to inefficient utilization of limited resources. To maximize the efficiency of aviation systems more accurate approaches are required to increase the predictability of these variables. One of these variables, wind aloft is analyzed in this study, with altitude, season and location, based on data obtained from eight radiosonde stations operating in Turkey. It is found that as altitude increases, wind direction approximates to 270°. Wind speed appears to be quadratically (or cubic for higher accuracy) proportional to altitude and maximum average wind speed is observed in March. In addition, relative humidity decreases linearly with an increase in altitude at an average of 4% per kilometer.

Keywords: Wind speed, Wind direction, Humidity

1. INTRODUCTION

Understanding airborne ambient conditions is of paramount importance for aviation. Of these, wind speed and direction are essential for the safe and efficient use of an air space, as well as being the most unpredictable. Others, viscosity, temperature, pressure, density and humidity are important for aircraft flight, engine performance, fuel burning and emissions. Flying at higher cruise altitudes as much as possible, or making use of tailwinds (when available) and avoiding headwinds (except during takeoff and landing phases) usually leads to fuel savings. Generally, proportional to fuel consumption, emissions of aircraft engines contribute significantly to harmful pollutants in the environment. Moreover, these impacts show a distinct feature that other anthropogenic emissions sources do not. This being emissions at various levels of the atmosphere, mainly at troposphere and lower stratosphere.

Vertical profiles of temperature, humidity and wind are investigated by radiosonde devices [1,2], research aircraft [3,4], unmanned aerial vehicle (UAV) [5,6] generally within the atmospheric boundary layer or by satellites. These observations are mostly used to understand chemistry of the atmosphere and trends in climatic characteristics.

These data and their vertical profiles are also important for the aviation. For instance, wind speed and direction strongly affects the fuel consumption and flight time of a large aircraft. According to a study, the effect of wind (combined with temperature) on fuel consumption can be as high as +1.4% and +2.3% for the westbound (east to west) and +1% for the southbound flights, for a B747-400 [7]. While, many studies have been dedicated to mapping a ground wind profile for wind energy purposes [8–10], there have also been a number of studies focusing on wind effect estimations for various

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situations, such as the descent phase [11–13] or for flight range [14]. These studies help to minimize uncertainties encountered particularly during trajectory prediction investigations.

Accurate wind estimations also improve the capabilities and the navigation and guidance performance of a UAV, such as a better geolocation of a way point and a better estimation of crab-angle [15]. Wind is referred to be an important factor that affects the UAV trajectory and thereby the performance of the mission of the UAV [16].

This study has two objectives. The first relates to wind aloft. Wind is a key parameter for instrument flight procedure designers. The International Civil Aviation Organization (ICAO) suggests using, when available, statistical wind data for instrumental flight procedure designs. Therefore, for countries which have their own long-term wind statistics, procedures can be based on such wind data (e.g., the United Kingdom and France). For others, the ICAO recommends a wind model, $w=2h + 47$, which is based on only altitude, where w is wind speed in knots and h denotes altitude in thousands of feet [17]. Nonetheless, since the ICAO wind model is constructed to cover a relatively large region, there may be serious overestimations on wind speed for specific regions, due to concerns for flight safety. While these overestimations lead to inefficient utilization of air space, they do not provide additional safety. Therefore, investigations on relatively local wind variations with altitude are useful in order to use air space more efficiently.

Knowing the relationship between wind and altitude contributes to a better determination of the boundaries and protection areas around an aircraft's flight path. In this respect, in a previous study by the same authors, variation of maximum wind speed with altitude was investigated for Turkey [18]. Considering maximum wind speed values at each altitude and for each season, a linear regression model for wind based on altitude was developed; this being an accurate alternative for other existing wind model of the ICAO. Accordingly, up to 25,000 ft (inclusive) wind speed can be found by the equation $2h+26$, whereas above 25,000 ft, it can be found by the equation $h+50$.

In addition to wind speed, wind direction is also important. Unlike wind speed, changes in wind direction might have greater effects on protection areas around a flight track. Although the prevailing wind direction for a specific route is generally known, wind direction can be highly variable. Therefore, in instrumental flight procedure designs, wind direction is assumed as omnidirectional for safety concerns. For the same reason, the results of this study do not suggest any specific wind direction.

A second objective is to determine the variation of humidity at different altitude conditions. Bearing in mind that the reliability of certain humidity sensors that are used in radiosonde devices at higher altitude levels can be questionable [3], radio sounding provides cost effective, long-term and stable observations. Humidity not only plays an important role in climate, it may also affect engine power output, and in turn NO_x emissions, by absorbing combustion heat. Considering that the specific heat of water vapor is greater than air, combustion with humid air tends to produce lower flame temperatures. In addition, at higher equivalence ratios, water vapor tends to react with carbon to produce carbon monoxide and hydrogen [19]. However, the effect may be different depending on the combustor type, therefore, it might be difficult to ascertain the net effect of humidity. In leaner combustors, humidity may have no effect on engine power output or NO_x emissions, whereas for other types of combustors, flame temperature may vary significantly or NO_x emissions may reduce with an increase in humidity for the same combustor inlet temperature. In modern aircraft engines, fuel control units alter fuel flow to the combustion chamber in order to restore engine thrust when the humidity levels become significant. Therefore, knowing the humidity variation with altitude contributes to aircraft engine performance and NO_x emission models for flight conditions. Humidity effect on NOx emissions is discussed in Boeing Fuel Flow Method 2 [20], which is one of the well-established and extensively used emission calculation methods [21]. In this method, a parameter called as humidity ratio is required to calibrate sea level NOx measurements for a given altitude level. This ratio can be calculated by a number of parameters including ambient temperature, saturation vapor pressure and relative humidity. Accordingly, if there is no humidity measurements for a given altitude level, the method suggests to use standard atmosphere sea level value of 60%.

At the end of the study, correlations for wind speed and humidity are also developed.

2. MATERIALS AND METHODS

The data of this study was obtained from long-term radiosonde measurements. In radiosonde stations, a radiosonde device, equipped with a transmitter, ascends with a weather balloon and simultaneously measures and transmits parameters, such as temperature, relative humidity, wind and pressure, to a ground station. Measured values cover a vertical distance of the troposphere up to the 10 hPa, however the ascend frequency can be 2-4 per day [6]. Turkish radiosonde stations and their World Meteorological Organization identifications are given in Figure 1.

Figure 1. Turkish radiosonde stations (circle markers indicate stations close to the sea)

As can be seen from Table 1, the meteorological data, obtained from the Turkish State Meteorological Service, cover around 40 years of the measurements, with two exceptions of stations 17095 (5 years) and 17351 (26 years). There are total of 10,927,597 rows of data with measurement times concentrated at 0:00 h (51.17%) and 12:00 h (48.44%), while the remaining items of data were measured at various times. The dataset is evenly distributed among months and days. The statistical calculation were performed by a software package, IBM SPSS Statistics (version 22.0).

Table 1. Yearly data count

Year	Samsun 17030	İstanbul 17062	Erzurum 17095	Ankara 17130	İzmir 17220	Isparta 17240	Diyarbakır 17281	Adana 17351	Row total
1970	-	-	-	-	2,138	-	-	-	2,138
1971	2,104	4,308	-	3,712	2,181	1,684	1,874	-	15,863
1972	3,751	4,290	-	3,719	3,101	1,860	2,364	-	19,085
1973	3,810	4,236	-	3,566	3,933	1,998	2,132	-	19,675
1974	468	3,336	-	3,507	1,777	1,863	1,352	-	12,303
1975	3,372	1,855	-	3,743	3,257	2,250	2,154	-	16,631
1976	3,704	4,168	-	3,685	3,700	2,270	2,757	-	20,284
1977	3,874	3,896	-	3,585	3,443	2,248	2,045	-	19,091
1978	726	2,838	-	3,698	3,552	355	369	-	11,538
1979	1,978	2,282	-	515	2,613	2,234	996	-	10,618
1980	2,359	1,913	-	3,739	3,385	2,257	2,030	-	15,683
1981	4,129	1,905	-	3,775	3,645	3,292	3,176	-	19,922
1982	4,421	2,169	-	3,746	3,309	4,367	4,025	-	22,037
1983	4,483	1,946	-	3,738	4,188	4,315	3,843	-	22,513
1984	4,480	2,166	-	3,783	4,422	4,533	990	-	20,374
1985	4,503	2,170	-	3,744	4,429	4,534	554	255	20,189
1986	4,449	2,223	-	3,771	4,438	4,516	4,487	4,257	28,141
1987	4,294	2,220	-	3,778	4,436	4,486	4,517	4,469	28,200
1988	4,262	2,220	-	3,460	3,513	3,579	4,523	3,561	25,118
1989	4,488	2,190	-	3,616	450	4,332	4,495	4,413	23,984
1990	4,458	4,070	-	3,782	7	4,389	4,519	4,386	25,611
1991	4,498	4,472	-	3,846	4,215	4,021	4,391	4,388	29,831
1992	4,378	4,475	-	4,461	4,501	4,139	4,307	4,393	30,654
1993	4,482	4,448	-	4,431	4,130	4,162	4,456	4,452	30,561
1994	3,112	4,313	-	4,543	3,068	3,055	4,506	4,466	27,063
1995	77,303	81,406	-	96,798	86,134	75,759	80,774	97,781	595,955
1996	41,299	63,695	-	97,341	85,237	63,981	60,007	31,053	442,613
1997	54,959	68,228	-	81,363	84,387	45,830	42,416	52,185	429,368
1998	70,926	74,190	-	90,070	89,876	63,497	86,070	82,812	557,441
1999	79,590	78,851	-	88,636	102,538	78,207	73,592	87,724	589,138
2000	67,130	65,636	-	27,351	107,256	76,639	52,321	67,939	464,272
2001	112,236	106,778	-	98,144	114,821	92,551	105,945	109,087	739,562
2002	113,594	109,148	-	98,793	101,684	96,580	101,069	112,882	733,750
2003	113,997	121,179	-	106,883	114,002	103,114	108,398	118,823	786,396
2004	124,065	123,456	-	109,081	112,496	106,763	109,777	121,557	807,195
2005	122,805	122,766	-	107,224	122,331	105,364	110,056	120,322	810,868
2006	122,833	122,637	262	108,396	121,343	103,153	108,467	120,826	807,917
2007	116,694	121,191	81,041	107,861	119,975	99,479	104,416	118,891	869,548
2008	115,533	122,476	67,924	106,814	120,746	100,131	107,253	105,951	846,828
2009	118,445	119,908	88,903	103,974	115,708	101,671	105,508	116,427	870,544
2010	8,467	8,824	6,587	10,600	8,287	7,881	-	8,449	59,095
Total	**1,546,459**	**1,584,478**	**244,717**	**1,527,272**	**1,688,652**	**1,397,339**	**1,426,931**	**1,511,749**	**10,927,597**

Within the dataset, this study focuses on the variables of altitude, wind speed, wind direction, ambient temperature, ambient pressure and relative humidity. Data was collected from radiosonde stations and, during that time, there were eight active radiosonde stations distributed around Turkey. The analyses show that there are extreme cases at both ends in temperature, humidity and wind direction variables, which is believed to be due to technical logging faults on a minor scale. Therefore, a valid range for these variables is assumed as follows: i) +60°C> temperature>-100°C; ii) 100%< relative humidity<0%; and iii) 360°<wind direction. The removed cases are 551 for temperature, 483 for humidity and 5546 for wind direction, while a number of cases are invalid in terms of more than one property.

Wind speed and direction data is directly obtained from the dataset and investigated with altitude which is treated as a categorical variable. While this is also true for relative humidity (RH), another parameter, mixing ratio (MR), is also derived to account for ambient temperature and pressure on the water vapor absorbing capacity of the ambient air. The MR, defined as the ratio of the mass of water vapor mixed into the mass of dry air (g/kg), can be calculated as follows [22]:

$$MR = \frac{B \times P_w}{P_{tot} - P_w} \quad (1)$$

where the B value is 621.9907 g/kg for air, P_w is the water pressure (hPa), and P_{tot} denotes the total ambient pressure (hPa);

$$P_w = P_{ws} \times RH/100 \quad (2)$$

where P_{ws} denotes water vapor saturation pressure (hPa);

$$P_{ws} = A \times 10^{\left(\frac{mT}{T+T_n}\right)} \quad (3)$$

and where A, n and T_n are constants, T is ambient temperature (°C).

3. RESULTS AND DISCUSSION

3.1. Wind Direction

The variations of wind direction and speed with months and altitudes are illustrated in Figure 2. One general observation from Figure 2 is that wind direction steadily approximates towards 270° with an increase in altitude. The wind direction, at the lowest and the highest altitude levels for overall the average of all of the stations, is found to be 169° (±111) and 260° (±39), respectively. The higher standard deviation is due to relatively variable low altitude wind directions and tends to decrease with an increase in altitude. In addition, as altitude level increases, the change in wind direction between neighboring altitude levels decreases.

High altitude level wind directions are always closer to 270° (from west) in winter months compared to summer months. For instance, in 17095, the winter average wind direction is closer to 270° than for summer at an average of 25° throughout altitude levels. In certain stations (e.g., 17030 and 17062) and at about 5-10 km of altitude level, summer average wind direction can be observed to be slightly closer to 270° than for those in winter. In 17220, 17281 and 17351, on the other hand, the summer average wind direction at low altitudes is observed to be closer to 270°, with an average of 28°, compared to winter.

For a given altitude, wind direction does not change significantly between winter and summer months, except for the first altitude categories in certain stations. However, average wind direction for spring and summer months (04-09) appears to be statistically different than those for winter months.

For stations relatively far from the sea (see Figure 2e to h), wind directions for the first altitude category show considerable variation compared to neighboring altitude categories or between months. For the rest of the stations, which are close to the sea, the variability in wind direction appears to be smooth.

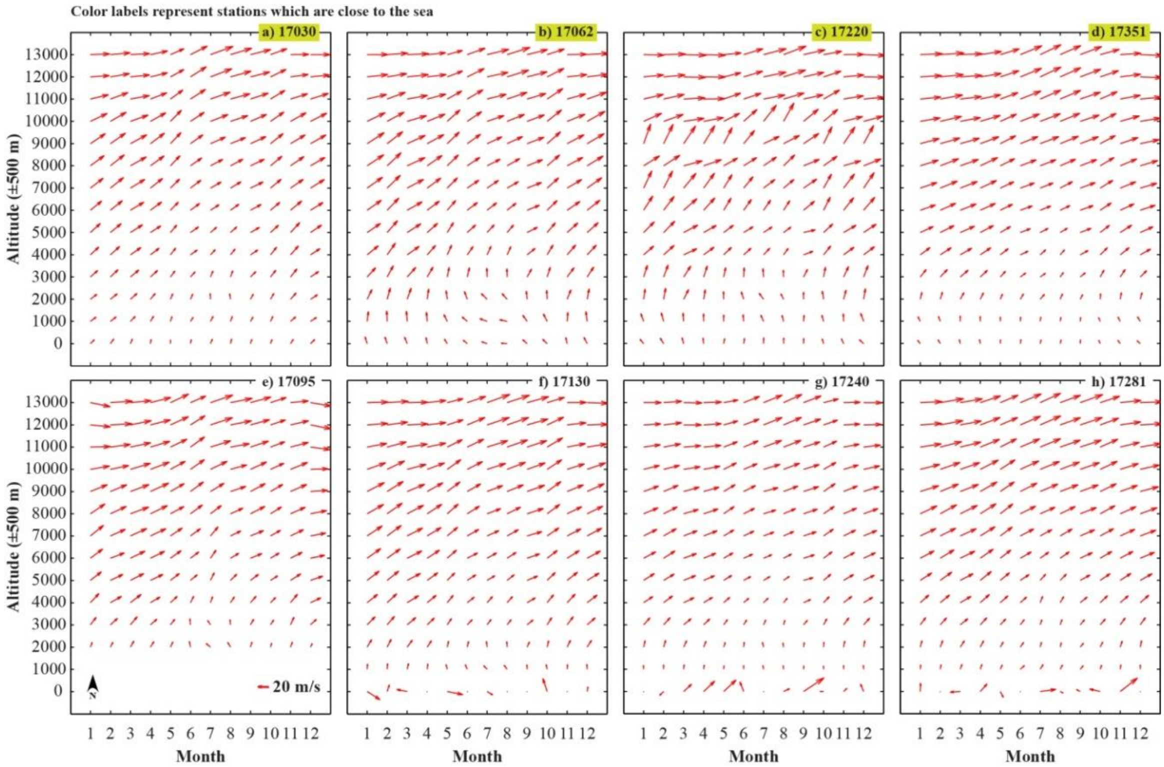

Figure 2. Variation of vector field of wind with month and altitude of the eight radiosonde stations

Referring to Figure 2c, an anomaly should be noted. For this station, the wind vectors patterns are significantly different than those for the other stations and do not follow the expected tendency at particular altitudes. The most abrupt change in wind direction is observed at around 9000 m of altitude. To address this anomaly, the data for this particular station was investigated in detail. Results indicate that: i) the wind direction data suddenly and substantially changes from 1994 to 1995 and the average of the wind direction (throughout the twelve months and for all altitude categories) before 1994 is about 23°, whereas it is 232° after 1995; and ii) for altitudes higher than 10,000 m, there is no wind direction data available before 1994. While the reason remains unknown, such a sharp increase in wind direction from 1994 to 1995 suggests a technical error. In addition, it should be noted that no such cases were detected for wind speed.

The first finding (i) explains why the wind direction vectors have lower degrees and show different patterns than expected. This is because when the average of wind direction throughout the years (1970 to 2010) are considered, the overall average is found to be relatively lower compared to other stations. The second finding (ii), on the other hand, can be used to justify why wind direction vectors above 10,000 m are restored, and how they are now similar to those for the other stations. This is because there is no wind direction data available before 1994 (that is thought to be unreliable) for above 10,000 m. This discussion concludes that the change in wind direction with altitudes appears to be noticeably similar for all of the radiosonde stations.

3.2 Wind Speed

Variation of the wind speed profile with altitude is illustrated in Figure 3. The first impression made is that wind speed varies with altitude in a monotonic manner and that the effect of altitude may be different for certain months. Maximum monthly average wind speeds are generally observed in March, up to an altitude of 10 km, followed by December, January and February, respectively. Above 10 km altitude, the highest monthly average of wind speed is observed in July and August, except for station 17351. Consideration of monthly variation of wind speed in a vertical axis reveals different patterns at different stations. In the following sections, wind speed is discussed for each station.

Station 17030 Samsun

Average wind speed changes between 8.5 m/s at ground level and 37.2 m/s at 13 km of altitude. Maximum wind speeds are observed in March (up to 10 km of altitudes) and June (above 11 km). The variation of average wind speed with per kilometer of altitude is higher at lower altitudes. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 15% up to 5 km of altitude, whereas it is recorded to be less than 5% above 11 km of altitude.

Station 17062 İstanbul

Average wind speed changes between 10.1 m/s at ground level and 35.1 m/s at 13 km of altitude. Maximum wind speeds are observed in March (up to 10 km of altitudes) and July (above 11 km), albeit they are close to March wind speeds. The variation of average wind speed with per kilometer of altitude is higher at lower altitudes. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 13% up to 5 km of altitude, whereas it is recorded to be less than 5% above 10 km of altitude.

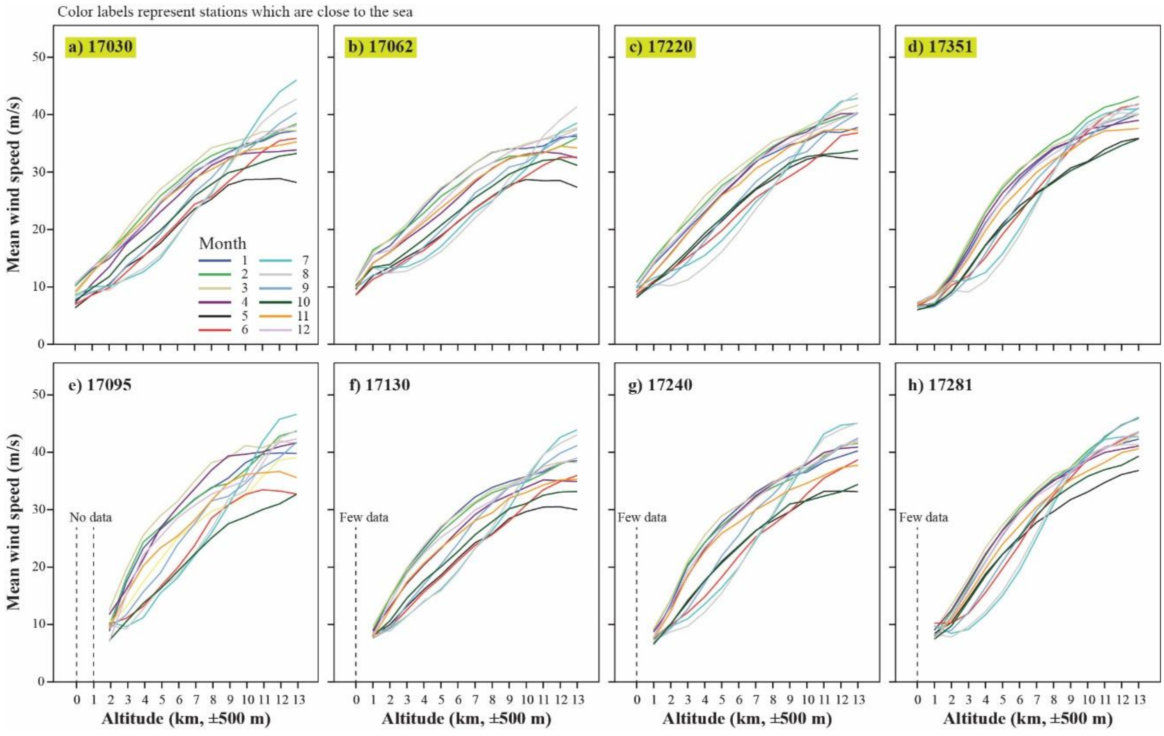

Figure 3. Effect of season on average wind speed – altitude relationship with stations (a-h)

Station 17220 İzmir

Average wind speed changes between 9.4 m/s at ground level and 39.0 m/s at 13 km of altitude. Maximum wind speeds are observed in March (up to 10 km of altitudes) and July (above 11 km), albeit they are close to March wind speeds. The variation of average wind speed with per kilometer of altitude is higher at lower altitudes. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 14% up to 5 km of altitude, whereas it is recorded to be less than 6% above 10 km of altitude.

Station 17351 Adana

Average wind speed changes between 6.7 m/s at ground level and 39.8 m/s at 13 km of altitude. Maximum wind speeds are observed in March (up to 6 km of altitudes) and February (above 7 km), albeit they are close to March wind speeds. The variation of average wind speed with per kilometer of altitude is higher at lower altitudes. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 15% up to 6 km of altitude, whereas it is recorded to be less than 6% above 10 km of altitude.

Station 17095 Erzurum

Average wind speed changes between 9.7 m/s at 2 km (no data available for ground level and 1 km of altitude) and 40.1 m/s at 13 km of altitude. Maximum wind speeds are observed in March (up to 10 km of altitudes) and July (above 11 km), albeit they are close to March wind speeds. The variation of average wind speed with per kilometer of altitude is higher at lower altitudes. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 13% up to 6 km of altitude, whereas it is recorded to be less than 7% above 10 km of altitude.

Station 17130 Ankara

Average wind speed changes between 8.4 m/s at 1 km (highly variable data at ground) and 37.7 m/s at 13 km of altitude. The maximum wind speeds are observed in March (up to 5 km of altitudes), in January (between 6 and 9 km of altitudes) and July/August (above 10 km), albeit they are close to wind speeds in March. The variation of average wind speed with per kilometer of altitude is higher at lower altitude. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 13% up to 5 km of altitude, whereas it is recorded to be less than 6% above 10 km of altitude.

Station 17240 Isparta

Average wind speed changes between 7.8 m/s at 1 km (highly variable data for ground level) and 40.3 m/s at 13 km of altitude. Maximum wind speeds are observed in March (up to 9 km of altitudes) and July/August (above 10 km), albeit they are close to March wind speeds. The variation of average wind speed with per kilometer of altitude is higher at lower altitudes. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 13% up to 5 km of altitude, whereas it is recorded to be less than 6% above 10 km of altitude.

Station 17281 Diyarbakır

Average wind speed changes between 8.5 m/s at 1 km (highly variable data for ground level) and 42.2 m/s at 13 km of altitude. Maximum wind speeds are observed in June (at 1 km of altitude), in March (between 2 and 8 km of altitudes) and February/August (above 9 km), albeit they are close to March wind speeds. The variation of average wind speed with per kilometer of altitude is higher at lower altitudes. The increase in wind speed with subsequent kilometers of altitudes appears to be higher than 15% up to 6 km of altitude, whereas it is recorded to be less than 7% above 10 km of altitude.

From the monthly wind speed analyses for individual stations, illustrated in Figure 4, it can be noted that the wind speed variation with altitude exhibits two profiles. While both profiles indicate a strong effect of altitude, for the summer months, (i.e., months 06-09), the wind speed increase with altitude remains at a moderate level for several of the first low altitude categories compared to other months, where the wind speed increase with altitude occurs at a rapid pace.

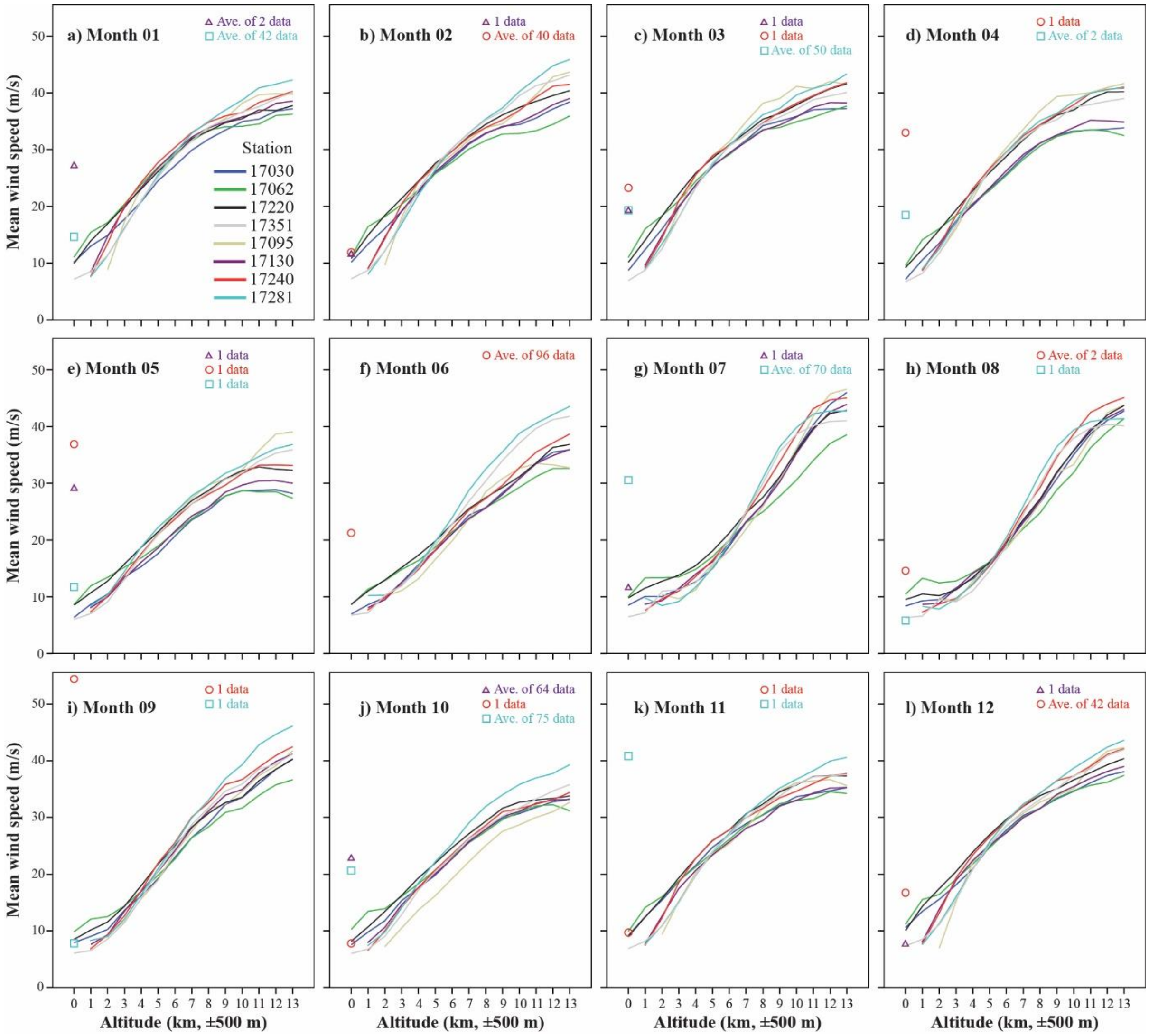

Figure 4. Effect of station on wind speed – altitude relationship based on monthly measurements (a-l). The symbols represent data anomaly due to low data for the corresponding station

3.3 Relative Humidity and Mixing Ratio

In Figure 5, the variation of relative humidity and mixing ratio are illustrated for a randomly selected year (2005) and month (May) for station 17130 at the 12:00h measurement period. Although, there is a strong tendency toward lower RH at higher altitudes, the effect of altitude on daily RH can be significantly variable. While on certain days a monotonic decrease in RH with an increase in altitude can be seen, significantly different variations in RH can be also observed. It should be noted that average standard deviations are around 5%, and are slightly higher for higher altitudes. The mixing ratio in Figure 5 is calculated using Eqs.(1-3). Depending on ambient temperatures, two sets of constants are used as the humidity, being assumed as water (between -19°C and +50°C) and ice (between -70°C and -20°), with the maximum errors of these constants given as 0.083% and 0.052%, respectively [22]. Unlike the RH, the daily average mixing ratio shows better correlations with altitude. While the correlation indicates an almost linear variation at certain altitude ranges, from an altitude around 5000-7000 m, the mixing ratios generally decrease to below 0.5 g/kg.

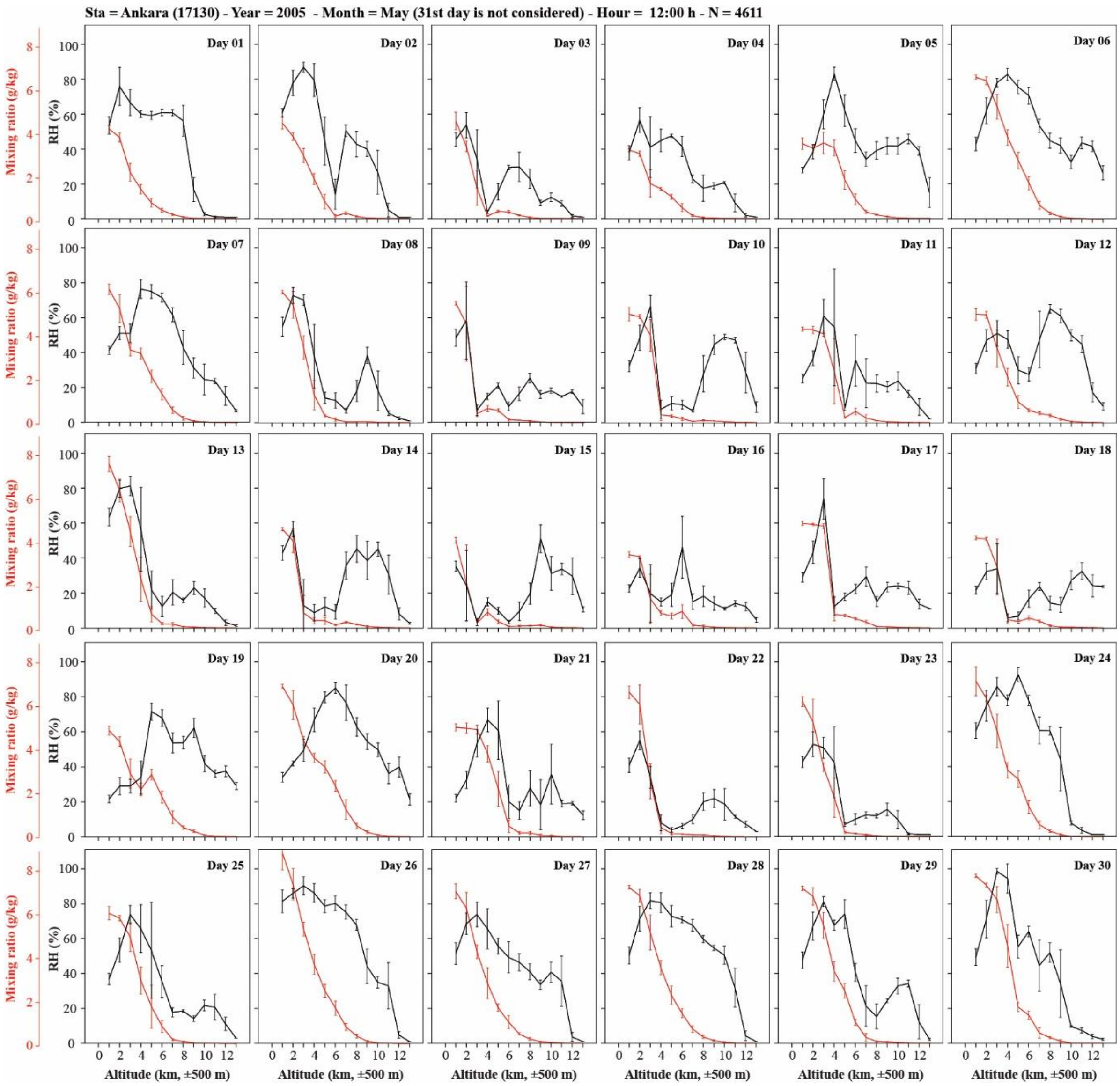

Figure 5. Variation of mean relative humidity and mixing ratio with altitude. Error bars represent 1σ

The daytime and night-time RH observations are also compared. Usually, night-time values are found to be higher than those for daytime. Independent *t* tests between these two periods suggest significant differences in the average of RH at different altitudes and months, where the night-time values are found to be an average of 3-4% higher compared to daytime values. Furthermore, the differences tend to be higher at ground level.

The effects of altitude and month on RH are illustrated in Figure 6. The first observation made from Figure 6 is that the humidity usually decreases with an increase in altitude. At certain stations, due to the fact that ground level humidity is relatively lower, the change in humidity may not be monotonic. Furthermore, the ground level humidity at stations located close to the sea are higher (ranging from 56% to 68%) than those for the other stations (ranging from 41% to 47%). Although it is far from sea, in one exceptional station, 17281, relatively higher humidity (52%) is observed, which can be attributed to the presence of local natural lakes and dam reservoirs around the station.

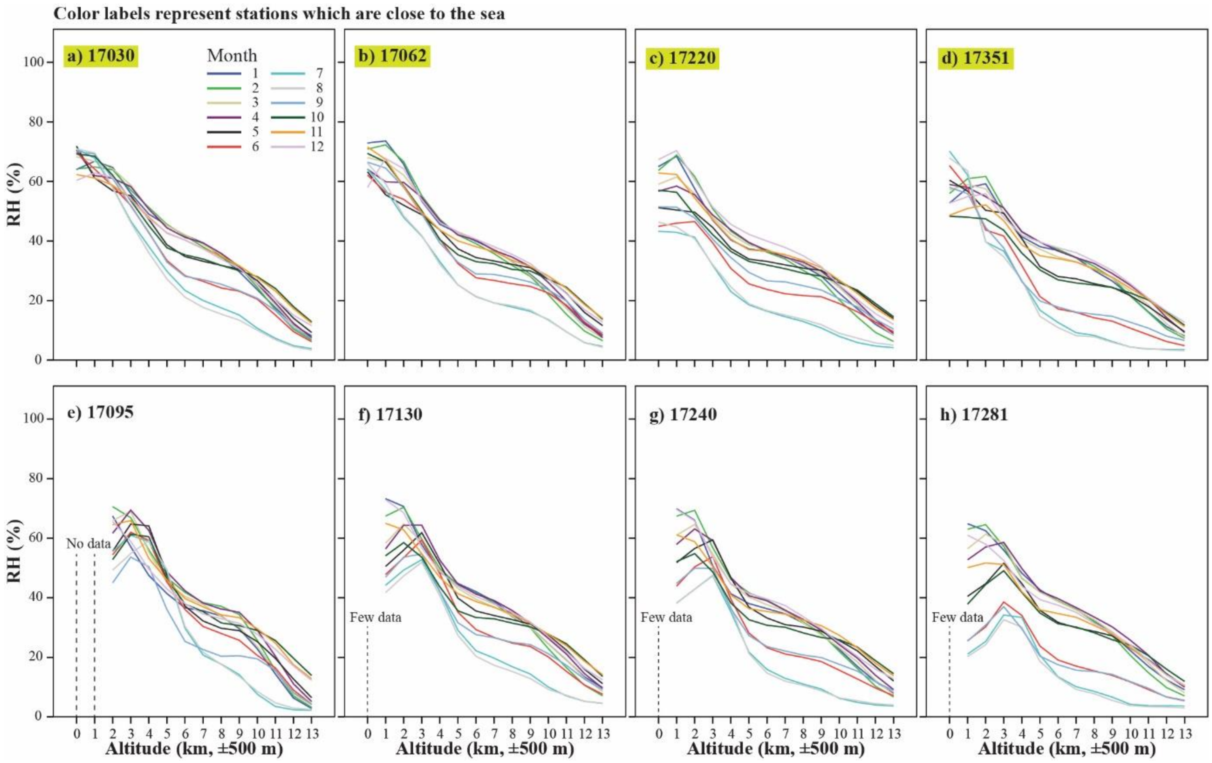

Figure 6. Variation of relative humidity with altitude and month for different radiosonde stations (a-h)

As shown in Figure 6 e-h, the lowest RH levels are always observed in July and August for altitudes equal to and greater than 7000 m. These results are also checked using the independent *t* test where the test results do not express significant differences in humidity between these months. For stations close to the sea, this result can even be lowered for altitudes of 1000-3000 m, depending on the station. Nonetheless, it should be noted that generally, airborne RH is observed to be lowest for the hottest summer months. This result can be extended as to the second and third lowest RH group for the months of June and September, and May and October.

The variation of MR with altitude and month for each station is illustrated in Figure 7 e-h. It should be noted that, the MR values steadily decrease with altitude up to 8000-9000 m, where it becomes negligible above these altitude levels. Furthermore, compared to the RH curves in Figure 6, MR curves exhibit a better and more predictable relationship with altitude and months. Unlike RH, the summer months (06-09) show higher MR. Independent *t* test results reveal that, up to 1000 m of altitude, the MR values at stations close to sea are higher than for other stations, whereas at higher altitudes of up to 5000 m there is an opposite trend ($p<0.001$). For the remaining high altitude categories, absolute MR values are so low that it is not possible to draw a statistically significant conclusion.

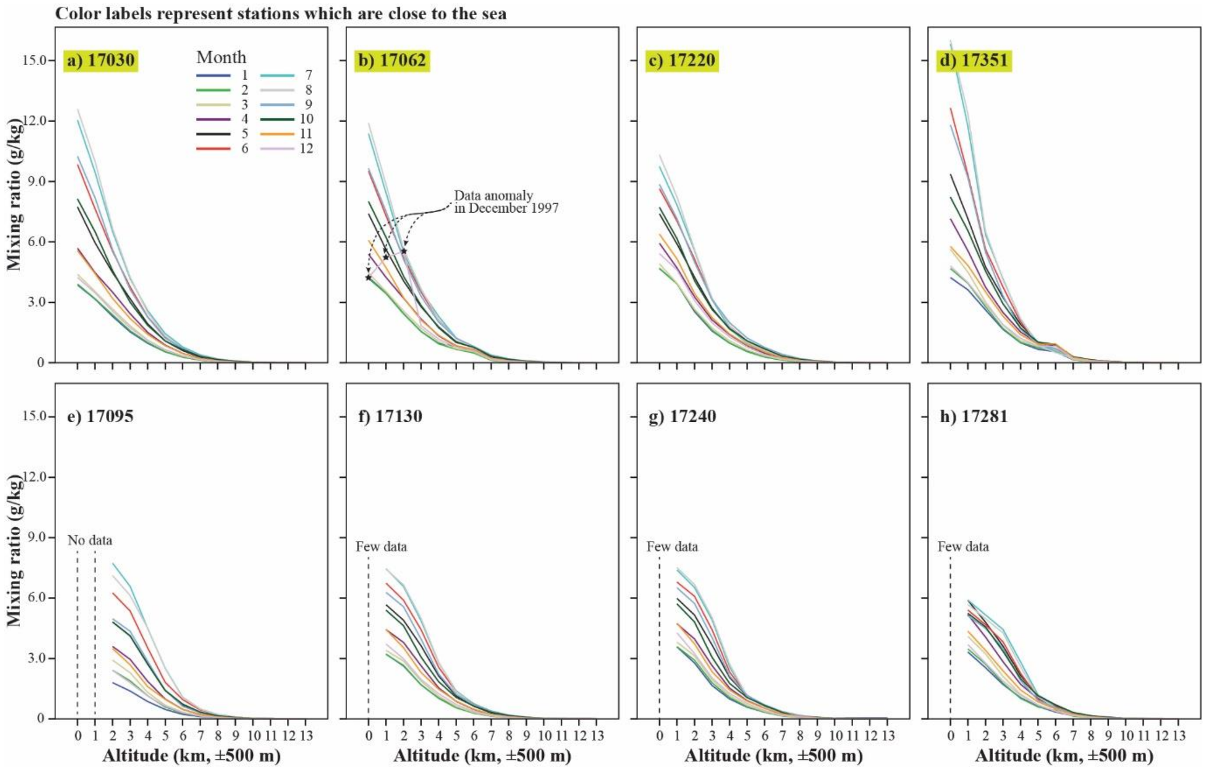

Figure 7. Variation of the mixing ratio with altitude and month for different radiosonde stations (a-h)

A data anomaly is detected for station 17062 and December. Referring to Figure 7b, it is observed only at the altitude level categories below 2 km (±500 m). An investigation into this anomaly reveals that it is caused by the data for 1997 only. When the 1997 data is excluded from the dataset, the average mixing ratio is calculated as 3.75 g/kg and 2.88 g/kg for 1 km and 2 km of altitude categories. However, for the dataset, including 1997 data, the same values increase to 3.97 g/kg and 4.17 g/kg, respectively. To address this anomaly, the RH, temperature and pressure values are also checked. While considerably lower values are observed for RH in 1997, the temperature and the pressure values are found to be significantly different compared to data for the other years. Numerically, the averages of temperature and pressure for all the years, except 1997, are calculated to be 1.4°C and 849 hPa, and -0.5°C and 830 hPa for 1 and 2 km of altitude, respectively. The averages of temperature and pressure only for 1997 are found to be 17.3°C and 459 hPa, and 9.2°C and 457 hPa for 1 and 2 km of altitude. These results indicate considerable high temperature and low pressure for corresponding altitude levels, which may be due to technical errors or being an extreme case.

Analyses also show that the wind speed and RH can be predicted, though within a large tolerance, depending on altitude, where average wind speed increases quadratically, while average RH decreases linearly with an increase in altitude. Bearing in mind that this study was not focuses on the modelling of the mentioned atmospheric parameters and comprehensive regression analyses were not performed, though it would be useful to develop general equations for these variables.

In this respect, results show that the relationship between wind speed and altitude can be quadratic (R^2=0.996) or a cubic function (R^2=0.999). The relationship may be even linear, if accuracy is not a major concern. The regression equations for the average wind speed and RH (R^2=0.981) is given as follows:

$$Wind\ speed\ (m/s) = -9.2 \times 10^{-8}[Altitude^2] + 3.7 \times 10^{-3}[Altitude] + 6.5 \qquad (4)$$

$$RH(\%) = -0.0041[Altitude] + 60.1941 \quad (5)$$

where the altitude variable is in meters. The first equation suggests that wind speed increases at an average of 2.3 m/s for each kilometer of altitude, and this increment decreases with altitude. Regarding the second regression equation, the ground level average RH can be noted at about 60%, as the International Standard Atmosphere (ISA) assumptions at ground level, and decreasing by an average of 4% with each kilometer increase of altitude. It should also be noted that the variation of RH with altitude at each individual station reveals a 3.6-5.2% decrease for each 1 km increase in altitude. For a typical cruise altitude of 11 km, it is found to be 16%. Similarly, a general regression equation for average MR may be given as follows (R^2=0.999):

$$MR(g/kg) = -7.8 \times 10^{-12}[Altitude^3] + 2.4 \times 10^{-7}[Altitude^2] - 2.4 \times 10^{-3}[Altitute] + 8.0 \quad (6)$$

where the altitude variable is in meters. However, it should be noted again that, despite highly significant R^2 values, these regression equations involve large tolerances, due to location, date and time, and care should be taken when drawing conclusions. Comprehensive regression analyses will be conducted in future studies.

4. CONCLUSION

Being two of the less predictable atmospheric parameters, wind speed and direction are of paramount importance for instrument flight procedure designers, airlines, pilots and air traffic controllers. Accurate wind estimations are also essential to improve the navigation and guidance performance of unmanned aerial vehicles. They may affect flight fuel consumption, flight time, cruise altitude and descent trajectory. In addition, to set protection areas around the flight trajectory of an aircraft, the wind speed and direction at corresponding altitude levels must be known. There are certain wind speed models providing wind speed prediction with significant overestimations to some extent. Nonetheless, regional wind speed models are thought to reduce these overestimations and to provide better utilization of air space. Humidity is also important, yet difficult to ascertain, particularly from an engine performance and NO_x emissions points of view.

This study describes variations of wind speed, wind direction and humidity, in Turkey, depending on altitude, location and season. A dataset, including almost forty years of statistical data, has been obtained from eight radiosonde stations operating in different regions of Turkey. It is found that average wind direction changes from 169° at the lowest altitude to 260° at the highest altitude. Unlike for the higher altitudes, at certain stations which are relatively far from the sea, wind direction at ground level is observed to be largely unpredictable. However, predictability substantially increases for these stations relatively close to the sea.

Maximum monthly average wind speeds are generally observed in March, up to an altitude of 10 km. Average wind speed at 13 km of altitude can be between 35 m/s and 42 m/s, depending on location.
While daily relative humidity may be highly variable, there is a strong tendency toward lower relative humidities at higher altitudes. The lowest relative humidities are observed in July and August for altitudes equal to and greater than 7 km. Moreover, night-time relative humidity measurements are found to be on average 3-4% higher than those for daytime measurements.

Since ambient pressure and temperature are also taken into consideration, a mixing ratio reveals a better relationship with altitude. Unlike relative humidity, the summer months reveals higher mixing ratios.

Lastly, general regression equations for wind speed, relative humidity and mixing ratio are developed with altitude being an independent variable. As a result, it should be noted that average wind speed increases by 2.3 m/s, while average relative humidity decreases by 4%, for an increase of one kilometer in altitude.

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