Atmospheric subsidence and the surface temperature variability in the pre-monsoon month over a semi-arid north peninsular Indian station: A case study

S M Deshpande, J R Kulkarni, R R Joshi, N Singh, S H Damle & G B Pant
Indian Institute of Tropical Meteorology, Pune 411 008, India

Received 17 January 2006; revised 21 September 2006; accepted 6 December 2006

Variability in maximum temperature in the month of March 2004 over Pune, a station representative of semi-arid region of north peninsular India, has been studied. The vertical wind velocity data measured by UHF wind profiler, installed at Pune (18.31°N, 73.58°E) has been utilized. Hourly averaged vertical wind velocity profiles were obtained four times a day, on a three hourly basis from 0800 to 1700 hrs IST (Indian Standard Time) in March 2004. The vertical velocity is found to have a typical mean and standard deviation of 10 and 15-20 cm/s, respectively. The mean structure of the vertical distribution showed predominately upward motion extending up to 2-3 km and predominately downward motion in the 3-6 km layers. After removing the effects of radiative and advective heating, the anomalies in the maximum temperature over Pune are found to be statistically related with the depth of the atmospheric column over which the subsidence occurs.

Keywords: Wind profiler, Vertical velocity, Subsidence depth, Temperature anomaly

PACS No: 92.70.Cp; 92.60.Gn

1 Introduction

‘Heat wave’ is one of the hazardous weather conditions in the pre-monsoon season (March-May) and early part (June and July) of south-west monsoon season over the Indian subcontinent. As per India Meteorological Department's definition, a region (or a station) is said to be in the grip of “Moderate heat wave” when the recorded maximum temperatures are above normal by 6-7 °C and it is called "Severe heat wave" if the maximum temperature is 8 °C or more above normal. The monthly distribution of number of heat waves shows bimodal distribution with peaks occurring in the months of March and June1.

March 2004 witnessed the above normal surface temperatures over most parts of India. Figure 1 shows the distribution of mean anomalies of the surface temperatures during March 2004 over India. The largest anomaly (3.5 °C) was observed over the extreme north-west India. Except a small region over the east peninsular India, the anomalies were positive everywhere. Figure 2 shows the time series of observed daily maximum temperatures over Pune (18.31°N, 73.58°E) during March 2004. The dark line shows the climatological mean value. It is seen that except for two days, on every day of the month the daily maximum temperature was above normal.

The favourable factors for heat wave conditions to occur over a particular region are: (1) large region of warm dry air prevailing in the area surrounding that region and appropriate flow pattern for transporting hot air into the region of the study, (2) absence of moisture over a depth of atmospheric column and (3) large amplitude anticyclonic flow in the vertical levels above a place2. The anticyclonic flow pattern in the
vertical produces a chain of processes for generation and maintenance of the heat wave conditions. First it produces a large-scale subsidence which makes the atmospheric column stable. The stability of the atmosphere inhibits the formation of clouds and horizontal and vertical transport of heat. The clear sky conditions help the surface to get more irradiance, which increases the surface temperature. Black et al. [2] (2004) have discussed about the factors contributing to the summer 2003 European heat wave by examining the large-scale atmospheric flow and the regional heat budget from ECMWF (European Centre for Medium Range Weather Forecast) analyses and measurements of the surface energy budget at Reading. Grazzini et al. [3] (2003) have also discussed European 2003 heat wave in a more quantitative way. Balafoutis and Makrogianiss [4] (2001) have analyzed a heat wave phenomenon over Greece during August 1999 mainly from synoptic point of view and it’s implications for tourism and recreation. It was found that the large scale downward vertical velocities (maximum value + 4hP/h) dominated over central Mediterranean and Balkan Peninsula. The tropospheric air above these areas is warmed up significantly, due to the adiabatic compression. This contributed to the observed intensive temperature rise at the surface and the absolute stability in the troposphere.

Thus the key factor in the process is the subsidence, or in more general terms 'vertical velocity'. The vertical velocity generally can not be measured and therefore has to be estimated using pressure and wind relationships (see e.g. Blake et al. [5]). Such estimated vertical velocities are found to contain large errors [6].

Direct measurements of the vertical velocities became available at Pune after installation of UHF wind profiler radar. Climatologically, duration of the heat wave over the country is generally 5-6 days and there are two or three such episodes. March 2004 showed similar behaviour and there was a long spell of nearly one month duration of above normal temperatures, similar to that shown in Fig. 2. The vertical velocities measured in the month of March 2004 have been used to understand the maintenance of the long spell of above normal temperatures over Pune. The paper is divided into four sections. Section 2 provides the brief details of the wind profiler system and the data used. Section 3 gives the results and discussion. The conclusions are given in Section 4.

2 Wind profiler system and data

2.1 Wind profiler

A 404 MHz UHF Wind Profiler/Radio Acoustic Sounding System (WP/RASS) fabricated by the Society for Applied Microwave Electronics Engineering & Research (SAMEER), Mumbai has been commissioned for utilization in the R & D mode at the India Meteorological Department (IMD), which is being operated jointly by IMD and Indian Institute of Tropical Meteorology (IITM), Pune. Regular observations with the system have commenced since June 2003. The system has typical height coverage of 6-10 km (depending on weather conditions) with a height resolution of 300 m. The wind profiler has (average) power aperture product of around 2 × 10^5 Wm^2. It has two off-zenith beams: east and north and one zenith beam setting, enabling measurements of all three components, viz. zonal, meridional and vertical of a vector wind.

The return signals in radar system depend on the backscatter through Bragg scattering from turbulent fluctuations in radio refractive index in the neutral atmosphere which are caused by clear air density fluctuations and/or by Fresnel scattering [7, 8]. The mean wind at any given height carries these fluctuations/irregularities and thus the latter (and hence the backscatter signal) becomes a tracer of the mean wind velocity at that height. One set of vector wind profiles is obtained in about 6 min, depending on the dwell time utilized for each radial beam measurement. The
technical specifications of the Pune Wind Profiler system are given in Table 1. System details inclusive of quality control procedure for data, validation of the wind profiler data products with the other conventional instruments, viz. RS/RW and pilot balloon are given in Pant et al. 10.

2.2 Data
The radial velocity values for each beam obtained for a given range bin, over the total observational period are passed through a process of consensus averaging11,12, which helps to eliminate to a large extent the effects of transients, interfering signals, outliers and random “spiky noise”. The radial velocities are sampled at 2-6 s intervals, depending on (1) system pulse repetition period, (2) number of coherent, incoherent integrations and (3) number of FFT points. The radial velocities which pass through a process of consensus averaging are then used to calculate the zonal, meridional and vertical wind velocities, representative of the mean wind in the hour of the observation. A vector wind profile is obtained typically in five to six minutes.

In the present study, the vertical velocity data measured by the wind profiler (henceforth referred to as ‘profiler velocity’) in the month of March 2004 is utilized. Hourly averaged profiler velocities were obtained four times a day, viz. at 0800, 1100, 1400 and 1700 hrs IST. The data were available for 81 observations out of a total maximum of 124. The velocities are then converted to meteorological convention in z-coordinate system \( w = \frac{dz}{dt} \), i.e. positive vertical velocity means upward motion. The data of daily maximum temperature of Pune in the month of March 2004 have been collected from the bulletin of Daily Weather Report published by India Meteorological Department.

### Table 1 – Technical specifications of the wind profiler system

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating frequency / bandwidth</td>
<td>404.37 MHz / ± 0.250 MHz</td>
</tr>
<tr>
<td>Pulse repetition period</td>
<td>60 µs / 160 µs</td>
</tr>
<tr>
<td>Pulse width</td>
<td>2 µs (uncoded); 16 µs (8bit coded)</td>
</tr>
<tr>
<td>Peak transmit power</td>
<td>16 kW</td>
</tr>
<tr>
<td>Duty ratio</td>
<td>10% Maximum</td>
</tr>
<tr>
<td>Number of coherent integration</td>
<td>76</td>
</tr>
<tr>
<td>Number of incoherent integration</td>
<td>10</td>
</tr>
<tr>
<td>Number of FFT points</td>
<td>256/512 (selectable)</td>
</tr>
</tbody>
</table>

3 Results and discussion

3.1 Role of advection in the surface temperature variability
Generally heat waves develop in the north-western parts of India, or northern parts of Pakistan. From these areas, waves expand to the neighboring subdivisions of the country. There are two approaches for understanding the surface temperature variability, viz. (i) physical and (ii) dynamical. In the physical approach, the surface temperature at any place is determined by surface energy balance, which is very complex due to processes related with net radiation, soil moisture and clouds. This requires measurements of incoming and outgoing radiations, soil properties such as type, depth, heat conductivity, amounts of cloud cover, etc. In the dynamical approach, the temperature variability is determined by the processes of advection, adiabatic and diabatic heating. The variability in incoming solar radiation is the main diabatic-heating factor governing the annual cycle of surface temperature variability.

Figure 3 shows the climatological latitudinal distribution of incoming solar radiation in the month of March. The figure is based on the data given by Iqbal13. In spite of large solar radiation in the southern parts of the country, the higher temperatures are observed over the northern parts of the country. The reason for this type of temperature distribution lies in the land-sea distribution. In the southern part of the country, the land area is less and is surrounded by the sea, viz. Arabian Sea in the west and Bay of Bengal in the east. The oceans have smoothing effect on the
range of maximum-minimum temperatures. On the contrary, in the northern regions, the stretch of land is more and being away from the sea, typically has less moisture. So the temperatures can attain higher values due to intense ground heating and resulting large sensible heat flux.

Figure 4 shows the latitude-time cross-section of the maximum temperature distribution. For preparing this diagram, the daily maximum temperatures at stations located at different latitudes in March 2004 have been considered. The data have been taken from Indian Daily Weather Report published by India Meteorological Department. The stations are New Delhi (28.37°N, 77.12°E), Jodhpur (26.18°N, 73.1°E), Allahabad (25.28°N, 81.44°E), Varanasi (25.20°N, 83.54°E), Nagpur (21.09°N, 79.03°E) and Pune (18.31°N, 73.58°E). There is zonal symmetry in the temperature distribution. Therefore the stations, even though not located at the same longitude, are able to capture the meridional distribution of temperature without large error. The tilting of temperature isolines indicates that the high temperatures are developed first in the northern latitudes and gradually move towards the southern latitudes.

Three episodes are clearly seen. In the first one i.e. on 4 March 2004 a region of high temperature is developed at latitude 28.31°N and after 5 days the high temperatures are observed at 18.53°N on 9 March. The second episode is from 16 to 20 March and the third episode from 23 to 27 March. There was an advection of warm air from northern to southern latitudes. The advection is caused by the prevailing northerly winds in the western part of the surface low-pressure area. The effect of advection is to make the temperature distribution uniformly high.

3.2 Role of subsidence in the surface temperature variability

In order to quantitatively understand the role of subsidence, in the surface temperature variability, the variability in the vertical motion has been studied. In the past, researchers used to estimate the vertical velocities by computing horizontal divergences from sparsely distributed RS/RW stations. The conditions improved a lot with the formation of National Center for Environmental Prediction (NCEP). A large quantity of conventional and non-conventional meteorological and oceanic data goes into the objective analysis of the NCEP general circulation model. The NCEP reanalyzed data have been widely used in the meteorological studies.

Figure 5 shows the distribution of anomalies of vertical motion at 500 hPa during the period 17-20 March 2004 derived from NCEP reanalysis. The anomalies are based on the daily grid point departure values from the climatological normal. The climatology of the vertical motion at 500 hPa has been prepared using the data of March 17-20 for the period 1948-2003. The vertical motions shown are the omega values in units of Pa/s. The large-scale subsidence at 500 hPa is seen to prevail over most parts of India. This is consistent with the earlier observations of close association between anticyclonic flow and heat wave/surface high temperatures by Chaudhury et al.\(^2\) Figure 6 shows the height-time cross-section of profiler vertical velocity. The dates are plotted from 10 March 2004 onwards because of the availability of continuous profiler data. The subsidence prevailing over the shallow convection is clearly seen.

Figure 7 shows the monthly mean of vertical distribution of profiler velocity at four observational hours (0800, 1100, 1400 and 1700 hrs IST). Figures 8(a) and 8(b) show variation of profiler velocity during 3-30 March 2004 at 1100 hrs IST. The figure also includes the NCEP reanalysis velocities reported at 06 GMT (1130 hrs IST) at the grid point located near Pune. The NCEP reanalysis vertical velocities (referred as ‘reanalysis velocities’ henceforth) are converted to cm/s from Pa/s for the sake of easy comparison. The heights of isobaric levels are computed in km using standard formulations. It is seen that the profiler velocity is one order higher than the reanalysis velocity most of the times. The profiler velocity is also seen to have larger variability in time and height than the reanalysis velocity. The reason for the large difference may be attributed to the fact that the reanalysis velocity is representative of synoptic scale motion, whereas the profiler velocity is representative of mesoscale motions. This is in
Fig. 5—Distribution of anomalies of vertical velocities (Pa/s) at 500 hPa during the period 17-20 Mar. 2004 [Anomalies are computed using NCEP reanalysis data.]

Fig. 6—Height-time cross-section of profiler vertical velocities (cm/s) during the period 10-31 Mar. 2004 [Each day consists of four observations. The subsidence prevailing over the shallow convection is clearly seen, e.g. 14 and 20 March; it is shown by the downward arrow above the heights 2.25 km and 1.35 km, respectively.]
agreement with the findings given by Nastrom and Gage\textsuperscript{14}, who observed that the profiler velocities were higher by nearly two orders than those estimated by adiabatic, kinematic and quasi-geostrophic omega equation methods. Schafer and Avery\textsuperscript{15} identified two potential causes for the discrepancy between profiler and reanalysis velocities. The first of these is related to different spatial and temporal characteristics of the reanalysis and wind profiler data. The second cause is the geographical sparseness of rawinsonde data and not assimilating wind profiler observations.

From Fig. 7(a), it is seen that in the morning hour, i.e. at 0800 hrs IST, the upward motion of the order of 5-10 cm/s occurs from surface to 3 km and the subsidence of the order of 1-2 cm/s prevails in the layer 3.5-5.5 km. The upward motion in the lower levels may be due to ground heating by solar radiation. The Standard Deviation (SD) is of the order of ±15 cm/s and is higher in the layers from 3.0 to 5.5 km. At 1100 hrs IST [Fig. 7(b)], the subsidence extends down to 2 km level and the upward motion is confined to the lowest level. The variability at lower levels is also seen to be increased, (SD = ± 20 cm/s).

In the afternoon hours, i.e. at 1400 hrs IST [Fig. 7(c)], subsidence has intensified to 10 cm/s. The standard deviations are also increased, reaching ± 30 cm/s in 1.5-4.0 km levels. The upward motion at the lowest level is also strengthened to 10 cm/s. At 1700 hrs IST [Fig. 7(d)] the upward motion in the lower levels extends up to 2.3 km, the subsidence motion prevails in the layer 3.0-5.5 km.

Blake et al.\textsuperscript{6} observed two-cell structures in the vertical over the Saudi Arabian heat low region: (1) the lower, shallow cell has surface convergence, rising air and divergence at 850 hPa and (2) the upper deeper cell has descending motion. They used radiosonde data for computing the divergence and vertical velocities. The vertical distribution of profiler mean velocity is in agreement with the two cell structure shown by Blake et al.\textsuperscript{6}.

The upward and downward motions can be considered to cause the cooling and warming effects on the surface heat budget and hence on the temperature. The upward motion mixes the air in the lowest levels and thus tries to prevent the surface temperature becoming high. The subsidence motion nullifies this moderating effect. In the presence of subsidence, the air is warmed by dry adiabatic lapse rate. The atmosphere becomes stable and convection-free. Clear sky leads to high incoming solar radiation.
at the surface and hence increases the surface temperature. As seen in Fig. 8(a) and (b), the subsidence motion is not occurring continuously, but there are layers of upward and downward motions laid on each other. This is in agreement with the dynamics of the atmosphere, i.e. Dynes compensation principle, which states that the boxes of convergence and divergence are laid on each other. This feature is not observed in reanalysis of wind structure and the reason for that may be attributed to the fact that in NCEP the computations of vertical velocities are carried out for discrete layers of the atmosphere of relatively large thickness, in which the fine structures are averaged out.

The factors governing the variability of surface temperature are: (1) radiation, (2) advection and (3)
subsidence. The advection dominates in the initial period. When the horizontal temperature gradient vanishes, the effect of advection becomes small. For quantifying the effects of these factors, the daily departures of maximum temperatures from the climatological normals are computed. These form “daily anomalies” in the maximum temperatures. During the month of March 2004, there was progressive increase in the incoming solar radiation as shown in Fig. 9 due to change in the solar declination. The incoming solar radiation at Pune has been computed using the formulation given by Racz and Smith\(^\text{16}\). The effect of the solar radiation on the variability of the temperature has been removed by fitting a straight line (shown in Fig. 9 by dotted line) to the daily anomalies in the maximum temperature and subtracting the contributions of the solar radiation heating obtained through the equation of the fitted straight line. The straight line fit captures most of the original variance (~95%) and represents a reasonable approximation to the original curve. The residual temperature anomalies can be thought to be arising from subsidence and noise.

As explained above, the subsidence occurs in the form of alternating boxes overlaid on each other. The total depth of the column, even if it is not continuous,
adds to the warming and stability of the atmosphere. Hence the association between total depths of the atmosphere over which the subsidence occurs (subsidence depth) and the temperature anomaly has been studied. The maximum temperature occurs in the afternoon hours. However the precursor to daily anomalies in the vertical wind may be seen in the vertical wind anomalies of the earlier hours. As the authors have observations at four different times in the day, (0800, 1100, 1400, 1700 hrs IST), the association between the maximum temperature anomalies at afternoon hour, and vertical wind anomalies at the four observational hours has been examined.

Figure 10[(a)-(d)] shows the scatter plots of maximum temperature anomalies and the subsidence depths at the four observational hours. The positive relationship is seen at all the hours. The correlation coefficients are 0.40, 0.39, 0.53 and 0.46 at 0800, 1100, 1400 and 1700 hrs IST, respectively. The values are significant at 5% level. The highest relationship is observed with the subsidence at 1400 hrs IST, which is quite obvious. The positive relationship of maximum temperature anomaly and subsidence at 0800 and 1100 hrs IST has potential application of local forecasting maximum temperatures 6 and 3 h ahead in time, respectively.

The study has shown a general positive relationship between the depth of the subsidence and maximum temperature variability over Pune, in the month of March. Though the results of the present study are

Fig. 10—Scatter plots of maximum temperature anomalies (°C) and the subsidence depths (m) at (a) 0800 (b) 1100 (c) 1400 and (d) 1700 hrs IST in March 2004 over Pune
based on the analysis of data of a single station (Pune), they may be considered representative of larger continental region especially over northern peninsula, because the atmospheric circulations and other topographic features are nearly same. Based on the above results the following qualitative picture of the maximum temperature variability in the pre-monsoon month of March, over the north peninsular region can be constructed.

In the beginning of March, the surface temperatures over the northern regions become high due to increased incoming solar radiation (compared to the previous month, i.e. February) assisted by extensive land mass away from the sea. This develops a shallow low pressure area at the surface over the heated region. The advection of warm dry air due to northerly winds increases the surface temperatures over the southern parts of India. Once the advection occurs, the temperature gradient reduces and then there is prevalence of uniform high temperatures over the country. The additional positive temperature anomalies are generated due to the atmospheric subsidence. The anomalies are found to be proportional to the total depth of the atmospheric column over which the subsidence occurs. The subsidence acts towards the increasing temperatures in two ways; (i) it prevents the upward motion in the lower levels from reaching higher heights, and thereby reducing the transport of heat and (ii) it warms and stabilizes the atmospheric column. The atmosphere becomes cloud free, which helps more solar radiation to reach the surface levels and increase the temperature.

Though many of the links in the above qualitative picture are described previously by Charney\textsuperscript{17}, the important link i.e. the positive relationship between the surface temperature and the subsidence has been established in this study. Though the study is based on one month’s analysis, it has used instrument-measured-vertical velocities for the first time. The skilful prediction of high impact weather is one of the greatest scientific and societal challenges of 21st century. The ‘heat wave’ is one of the high-impact weather phenomenon over India. A ten-year international research programme, viz. ‘The Observing-system Research and predictability experiment (THORpex)’ has been launched by the World Meteorological Organization/World Weather Research Programme (WMO/WWRP) to accelerate improvements in accuracy of short-range weather prediction models\textsuperscript{18}. The study has indicated that a simple regression model may be developed to forecast the maximum temperature anomaly at local scale a few hours ahead. This forecast would probably contain a certain degree of statistical error. The two-cell structure and the order of the vertical velocity brought out in this study will be found useful in the validation of the mesoscale models over the Indian region and in turn will be useful in improving the short range temperature forecasts over the region, and thus achieving the goals of THORpex.

4 Conclusions

The study has brought out the role of vertical velocities in the maximum temperature variability over a station, representative of semi-arid region. The vertical velocities used are obtained from the direct measurements by UHF wind profiler. The study revealed the existence of two-cell structure in the vertical wind velocity profile in the pre-monsoon season over India. The lower cell consists of upward motion extending up to 2-3 km and the upper cell of the subsidence motions confined between 3 and 6 km. In the morning hours, the upward motion in the lower levels extends to maximum height of about 3 km. With the progress of the day, the subsidence penetrates to the lower levels reaching around 1 km in the evening hours. This mean structure of the vertical circulation of the atmosphere is similar to that found by Blake et al.\textsuperscript{6} during summer MONEX period. However, large variations (standard deviation ~ ± 20 cm/s) are observed in the individual profiler velocity profiles.

The positive anomalies in the maximum temperature over Pune, in this month are related to the heating processes by advection, radiation and subsidence. There are three distinct episodes of advective warming, viz. during 4-9, 16-20 and 23-27 March 2004. After removing the effects of advection and incoming solar radiation, the variability in the anomalies in the maximum temperature is found to be related with the total depth of the atmospheric columns in which subsidence occurs. The unique vertical velocity data set obtained through wind profiler system has revealed the important role of the subsidence in the surface temperature variability quite explicitly.

Acknowledgements

The work was carried out as part of a project sponsored by Department of Science and Technology
(DST), New Delhi. Authors wish to thank India Meteorological Department for continuous support in acquiring the wind profiler data. The authors gratefully acknowledge NCEP for Reanalysis data used in this study provided by the NOAA-CIRES ESRL/PSD Climate Diagnostics branch, Boulder, Colorado, USA, from their web site at http://www.cdc.noaa.gov. They also thank the reviewers for their useful suggestions.

References
12 Barth M, Evaluation of real time quality control techniques applied to sub hourly wind profiler data, 9th Symposium on Meteorological observations & instrumentation, Charlotte, NC, 1995, 27.