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Harmonic analysis of 10-year ASOS data: The detection of the diurnal continental enhanced tide and eastward-propagating waves over the Great Plains and Midwest

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1. Introduction:

Diurnal solar heating is an important forcing for the Earth's atmosphere. In the upper troposphere and stratosphere, by heating the water vapor and ozone, the sun generates a global atmospheric tide. In the lower troposphere, because of the variable surface properties and terrain, inhomogeneous spatial heating generates mesoscale circulations with a local character, for example, plateau-plain circulation (Banta, 1984), mountain-valley circulation and sea-breeze.

The diurnal surface pressure variation is contributed by both the global migrating atmospheric tide and the diurnal mesoscale signal. The migrating tide moves westward with speed of the Sun. The diurnal tide has pressure phase around 105^{o} and amplitude about 20 Pascal in mid-latitude in Northern Hemisphere (Chapman and Lindzen, 1970). The local diurnal circulation generated by the diurnal mesoscale heating has a surface pressure signal that moves with the speed of gravity waves.

2. Data analysis methods:

A convenient way to monitor and classify the diurnal circulations is to isolate the diurnal component by harmonic analysis. The separated diurnal component can be expressed as amplitude and phase (Mass et al, 1991). The phase is equivalent to the time when the diurnal component reaches its maximum.

3. ASOS Observations:

Harmonic analysis has been applied to nearly 1000 ASOS over the CONUS. Over the Great Plains and the Mid-west, diurnal pressure phases show a tide pattern, with nearly homogenous phase, except an eastward tilt in pressure phase close to the Rocky Mountain. Also, the pressure amplitude (80~120 Pa) is much larger than the value predicted by the traditional tide theory (around 20 Pa). The diurnal surface temperature phase is around 220^{o}, and the amplitudes are about 3 K.

When we plot the amplitude of surface pressure and temperature changes according the longitude (Figure 1), we found that the pressure amplitude is actually tightly related to the temperature amplitude. Both of them are larger in the dryer elevated mountain states in the west. A plot (Figure 2) of diurnal pressure amplitude and temperature amplitude shows a clear linear relation: P=cT, with c around 15 Pa/K for both summer and winter. When we look at the phase distribution according to longitude, we see that the temperature phases (Figure 1) are nearly the same across the continent. So we assume that the continental enhanced tide is mainly contributed by the sensible heating near the ground and is proportional to the diurnal surface temperature variations. The increasing amplitudes toward west are because of the elevation, vegetation, and Bowen ratio.

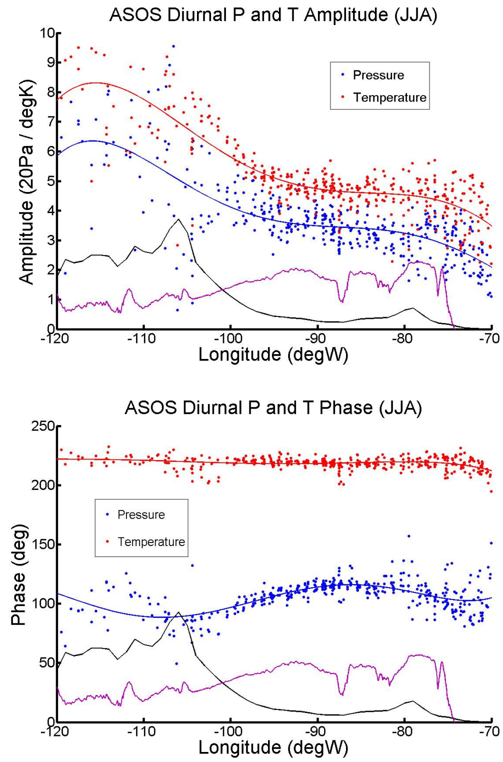

Figure 1: Pressure and Temperature Amplitudes and phases change with longitude for summer (JJA) and winter (DJF) over the CONUS

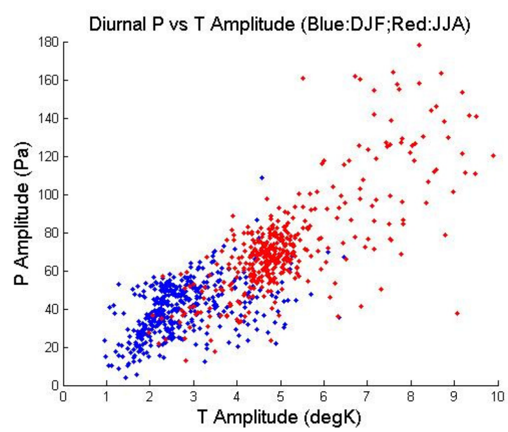

Figure 2: Pressure amplitude vs. temperature amplitude for summer (JJA) and winter (DJF).

Our key assumptions here is that the observed diurnal pressure signals over the Great Plains and the Midwest include two parts, the fast westward propagating part with the speed of the Sun, we call that part the Continental enhanced tide. Besides the tide, we assume that there also exist some eastward or westward propagating waves with slow phase speeds comparable to that of the gravity waves, propagating either east or west.

In order to separate these two parts, we utilized the Nelder Mead Simplex optimization method. We minimize $\sum(\vec{P}^{obs}{}_{D} - C\times e^{-i\theta}\times\vec{T}_{D} + A\times e^{-\mu\times Lon}e^{ik(Lon+\varphi_{0})})$ to get C, θ, A and k. Here "D" means diurnal. C is the conversion ratio for the amount of surface heating (in degK) into the pressure perturbation (in Pa). θ is the phase lag between the pressure maximum and the temperature maximum. μ represents the damping of the east (west) propagating waves away from the source. φ_0 is the starting phase east (west) propagating waves near the source. k is related to the phase speed of the presumed eastward (westward) propagating waves.

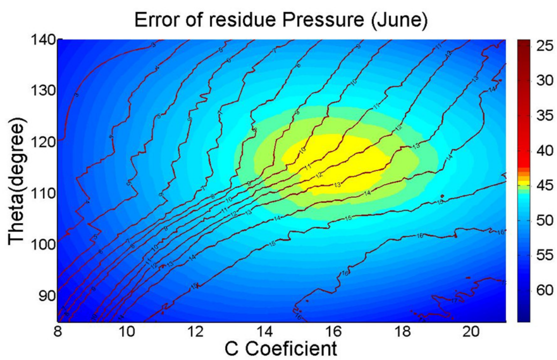

Figure 3: Optimization results for summer (JJA). Cost function is colored. Solid lines are the isolines of k.

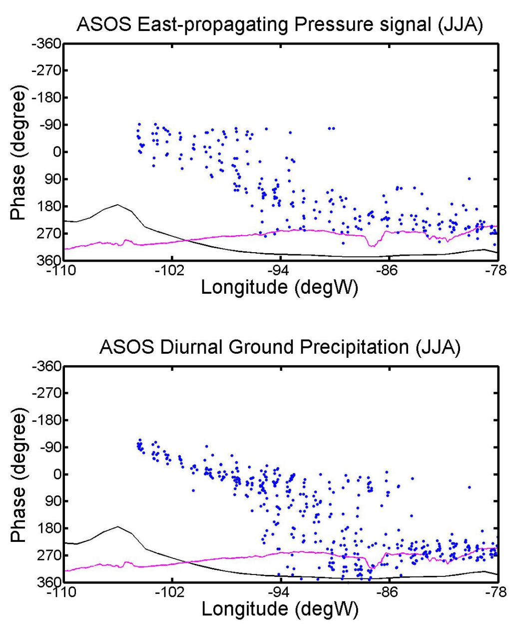

Figure 4: The Eastward Propagating Wave signal from the optimization result and the diurnal precipitation component for summer time (JJA) from ASOS data

The calculated results converge to a best solution (Figure 3). The continental enhanced tide part has phase about 105^{o} and amplitudes around 70~100 Pa. The propagating wave part is toward east with phase speed about 15m/s. The longitudinal phase distribution (Figure 4) of the diurnal precipitation component shows that the precipitation bands also moving toward east with speed around 15m/s. Our discovered east propagating waves are probably related to the east moving storms described in Carbone et al (2002). In our results, the precipitation phase is about zero degrees at 100W, and in Carbone et al (2002), the storms start at midnight east of the Grand Junction. Our derived phase speeds for pressure signal and precipitation signal are similar to the propagating speed of the summer storms in Carbone et al (2002).

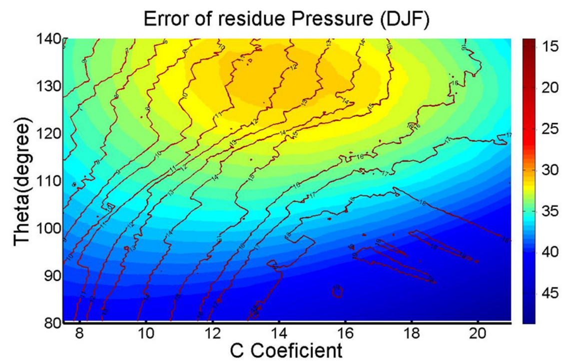

Figure 5: Optimization results for winter (DJF). Cost function is colored. Solid lines are the isolines of k.

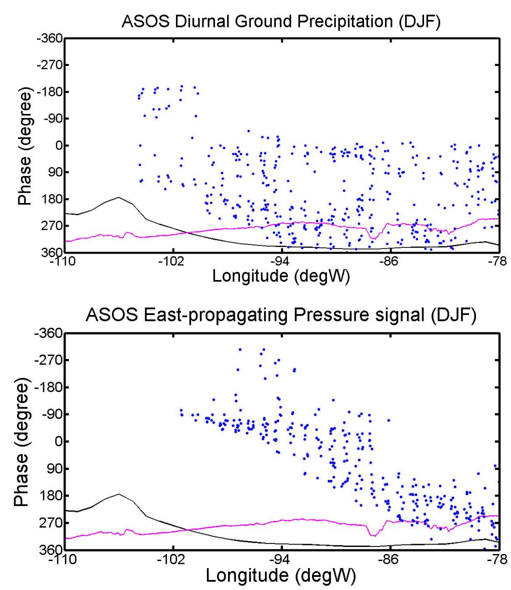

Figure 6: The Eastward Propagating Wave signal from the optimization result and the diurnal precipitation component for winter time (DJF) from ASOS data

The same optimization process is also applied to the winter time data to see if we could identify these two parts in the cold season. The calculated results also converge to one best solution (Figure 5). The results show that in winter time, there also exist an eastward propagating wave, but with phase speed around 20m/s, faster than that of the summer time. However, there is no corresponding east-propagating precipitation signal (Figure 6).

We conclude that the observed diurnal surface pressure is the summation of the continental enhanced tide and the east propagating pressure signal. The continental enhanced tide is mainly contributed by the sensible heating near the ground and is proportional to the diurnal surface temperature changes. The eastward propagating pressure signals exist the whole year. In summer time, the speed of this east propagating pressure waves and the precipitation bands match each other. But in winter time, there exist no this kind of east moving precipitation bands. It raises the question whether the east propagating pressure waves are the cause or the result of the east propagating precipitation bands, and if the precipitation is caused by the pressure disturbance, then what is the source of this east propagating pressure signal.

4. Linear model

In order to explain the diurnal continental enhanced tide and how the upper drifting PV triggers the convection in the lower part of the troposphere. A linear model with Boussinessq approximation and solved by the FFT method is deployed. Linear model can help us to explain the pressure phase physically, and test how pressure phases are modified by some environmental parameter like stability, horizontal and vertical heating scale, and Coriolis Effect, also environmental mean wind. Linear model can simulate both the global tide and the local mesoscale disturbance.

An isolated local diurnal heating will generate a pressure signal with relatively early phase at the heating center, then later and later phase away from the source. The derived phase speed from the phase tilt is comparable to the gravity wave speed estimated by the theory. Also away from the heating source, the pressure amplitude decays rapidly because of the damping. For local diurnal heating that reaches its maximum at noon, the generated phase at the center is about 40^o, which means the pressure reaches its minimum at around 3PM local time. Phases become later away from the source, which can be imagined as gravity waves propagating outward. The amplitude becomes smaller away from the heating source.

With migrating homogenous heating over the continent, the generated diurnal pressure variations over the continent present nearly constant phase over the whole continent except near the edge which represent the sea breeze effect. If we assume that the ground PBL heating reaches its peak one hour after noon, the phases for surface pressure are almost 105^o. Near the edge, pressure phases become later. This is consistent with the traditional tide theory and the observations. ASOS data also show that the diurnal pressure phases become later for the stations near the coast area.

Both the analytical solution and the linear model simulation results show that with the existence of the vertical mean wind shear, the potential vorticity pulses generated by the elevated diurnal heating can trigger convection in the lower troposphere downwind side even far away from the original source. The plot for pressure phase changes with distance shows that the diurnal PV-pulse is able to cause east-increasing phases. The phase speed derived from the tilt is exactly the same as the upper mean wind. The combined pressure signal for the two parts shows a longitudinal phase distribution similar to the surface pressure phase that we observed over the Great-plains and the Midwest. Besides that, the phase speed for the upper drifting PV and the vertical motion in the lower troposphere right below the shear are exactly the same and equal to the upper mean wind speed.

With mean wind but no vertical shear, the local diurnal heating will generate pressure signal with strengthened pressure amplitude in the downwind side. Compared with the shear case, the pressure phases around the heating source are similar to the case with shear. But in the far field, the pressure signal that generated by gravity waves become much weaker since gravity waves damped very fast away from the source compared with the vertical disturbances generated by the upper drifting PV for the shear case.

The linear model gives us some explanation about the mechanism and a proof of our tidal assumption for the ASOS data. We also utilized the linear model to test our optimization method. First, we assume that we know the pressure amplitude and phase distribution of the summation of the tide part and the east propagating pressure wave part. Following the same optimization process, we separate the surface pressure signals to two parts. The results show that the separated tide part and the east propagating pressure wave part are almost the same as what we set at the beginning. This test shows that the optimization method that we used is reliable.

5. NARR data:

A preliminary study of the 10-year NARR data helped us to test the PV mechanism. The results show that in summer time, the diurnal PV variation has a weak maximum band in the mid-troposphere extended from 650hPa to 450hPa, with peak at 500hPa. This PV maximum extend from 105W to 70W, almost reaches the east coast. The top of the Rocky Mountain is around 750hPa, so these elevated PV maximum band might be caused by the daily cumulus heating over the Rockies.

The vertical profile of daily mean easterly wind shows that there exists a gradually vertical mean wind shear from 2m/s in the lower troposphere to about 20m/s at 200hPa. The daily mean relative humidity (RH) shows that it is very humid (>50%) below 700hPa. Since the generation of thunderstorms requires two conditions: one is sufficient water vapor in the atmosphere; the other is scaled upward lifting. So in the summer time over the Great Plains and Midwest, the timing for the precipitation will mainly be determined by the initial time of the vertical disturbance.

When we plot the PV phase at the conducting level (500hPa) together with the W phase at the condensation level (775hPa), and the precipitation at the ground and the east-propagating pressure signal from the ASOS data, we see that their phase tilt are similar. So we propose one possible explanation here for the systematical diurnal east-propagating perception bands over the Great Plains and the Midwest: During the summer time, Rocky Mountain is an elevated diurnal heat source. The local convection that happens in the morning generates cumulus clouds and the PV pulse which extends to mid and upper troposphere. These PV pulses drift with upper steering wind around 500hPa level, and cause vertical motion in the lower troposphere because of the existence of the vertical mean wind shear. The vertical motions are strongest around the shear layer from 775hPa to 625hPa, and become weaker close to the surface. It explains why east of the Rockies, the summer thunderstorms could happen at midnight when the PBL environment does not favor the convection to happen.

In winter time, there is also a local PV maximum band around 700hPa to 400hPa with the peak at 550hPa. The PV phase at around 550hPa and the w phase at around 750hPa are similar. The value for PV maximum (0.01pvu) and W maximum (~0.001m/s) are much smaller compared with their summer time counterparts (0.06pvu, 0.04m/s). The daily mean relative humidity shows that in winter time, the lower troposphere is quite dry for the Great Plains and Mid-west area (~30%). So the timing for the diurnal convection is no longer tied to the phase of the vertical motions in the lower troposphere. Another reason is that in winter time the vertical motion generated by the upper drifting PV is too weak to cause any meaningful scaled lifting.

6. Conclusions:

Harmonic analysis has been applied to 10-year record from nearly 1000 ASOS over the United States to isolate the diurnal component of surface pressure, temperature, precipitation, etc. In warm season (JJA), for stations over the Great Plains and Midwest, the phases of the surface pressure component present a diurnal atmospheric tide pattern; with consistent phases around 105^o. The longitudinal variations of diurnal surface pressure amplitude are tightly related to the temperature amplitude, with the increasing amplitudes of both pressure and temperature toward west because of the elevation and vegetation. So we assume that there exists a continental enhanced diurnal atmospheric tide that is mainly contributed by the sensible heating from the ground and is proportional to the diurnal surface temperature variations. Optimization method has been used to separate the continental enhanced tide from other diurnal signals.

The residue parts of surface pressure show a clear east-propagating signal, with phases increasing eastward and the estimated phase speed about 15m/s. The phases for diurnal precipitation component also show increasing phases with longitude with a phase speed of nearly 15m/s. Our derived phase speeds for pressure signal and precipitation signal are similar to the propagating speed of the summer storms in Carbone et al (2002). In our results, the precipitation phase is about zero degrees at 100W, and in Carbone et al (2002), the storms start at midnight east of the Grand Junction.

The data from different months shows that the eastward propagating pressure signal exists almost the whole year, but the correspondence with the precipitation only happens in warm season (JJA). This result raises the question whether the eastward propagating pressures signal is the cause or the consequence of these eastward propagating precipitation bands and what is the source of these east propagating pressure and precipitation signals. In order to answer these questions, linear model is deployed and the results show that with the existence of the vertical mean wind shear, the potential vorticity pulse generated by the elevated diurnal heating (diurnal convection over the Rockies) can trigger convection in the lower troposphere downwind side even far away from the original source. The simulation results show that these PV-pulses generate an east-increasing diurnal surface pressure signal with phases similar to what we observed over east of the Rockies.

The analysis of NARR data confirms that in summer time, the Rocky mountain is an elevated heat source, the diurnal sensible and latent heating generate strong PV pulses (with amplitude around 0.06pvu) at around 500hPa, which drift with the steering wind, and trigger the vertical motion with peak around 775hPa. Since in summer time, the daily mean relative humidity is very high (~50%), even a moderate vertical disturbance (0.004m/s) will be able to initiate condensation and self-sustaining convection. The phase plot of diurnal upper drifting PV and lower vertical motions shows similar phase speed and consistent with that of the surface precipitation signal and the east propagating pressure waves from ASOS data. In winter time, the Rocky Mountain is still a diurnal heat source but much weaker. The diurnal sensible and latent heating variations are about half of the value of the summer time. The PV-pulse (the amplitude is around 0.01pvu) generated at the mountain top still drift eastward with the 550hPa steering wind, and generate even weaker vertical disturbance at 775hPa (0.001m/s), since the lower troposphere over the Great Plains is very dry, the timing for the precipitation is no longer tied together with the vertical motion generated by the upper drifting PV. But this east propagating signal still shows up in the surface pressure observations.

7. Acknowledgements:

This research was supported by the National Science Foundation, Division of Atmospheric Sciences (ATM-0531212).

REFERENCES

Banta, R.M. 1984: Daytime Boundary-Layer evolution over mountainous terrain. Part I: Observations of the dry circulations. *Mon. Wea. Rev.*, **112**, 340-356.

Braswell, W. D. and R. S. Lindzen, 1998: Anomalous short wave absorption and atmospheric tides. *Geophy. Res. Let.*, Vol. 25, No. 9, 1293-1296.

Carbone R.E., J. D. Tuttle, D. A. Ahijvych and S. B. Trier, 2002: Inferences of predictability associated with warm season precipitation episodes. *J. Atmos. Sci.*, 59, 2033-2056.

Chapman, S., and R. S. Lindzen, 1970: Atmospheric Tides. D. Reidel, 200pp.

Mass, C. F., W. J. Steenburgh and D. A. Schultz, 1991: Diurnal surface-pressure variations over the continental United states and the influence of sea level reduction. *Mon. Wea. Rev.*, **119**, 2814-2830.