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Using diurnal surface pressure variations to study atmospheric circulation in Owens Valley

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1. Phenomena:

Diurnal solar heating is an important forcing for the atmosphere. In the upper troposphere and stratosphere, by heating the water vapor and ozone, the sun generates the global atmospheric tide. In the lower troposphere, if terrain is inhomogeneous, mesoscale circulations can develop, such as plateau-plain circulation, mountain-valley circulation and sea-breeze. A convenient way to monitor and classify such circulations is by a harmonic analysis of pressure and temperature. In our work, harmonic analysis has been applied to nearly 1000 ASOS over the CONUS. Over the Great Plains and the mid-west, the diurnal surface pressure phase has the characteristic of a "continentally enhanced tide". By contrast, the large amplitude (150 Pa) and early phase (90 Degree) of some valley stations in summer season, such as Bishop and Blythe in California, and Rifle in Colorado draw our attention to the unique properties of the valleys in the western United States.

In association with the T-REX project in 2006 (Grubisic et al., 2005), sixteen Automated Weather Stations has been installed and maintained by the Desert Research Institute for a two year period (. Their fine spatial (distance between stations is almost less than 500 meters) and temporal resolutions (10 minutes) are very helpful to study the extreme diurnal surface pressure signals in Owens Valley, which is a good representative of the particular and dry valleys in the Western United States.

2. Data analysis methods:

By doing a harmonic analysis, we obtained the diurnal component of the surface pressure with their amplitude and phase distribution over the United States (Mass et al, 1991).

$$\mathrm{Re}_n = \sum_{k=1}^{N} P_n(k)\cos\frac{2\pi k\times 24}{N} \qquad \mathrm{Im}_n = \sum_{k=1}^{N} P_n(k)\sin\frac{2\pi k\times 24}{N}$$

$$C_n = \sqrt{\mathrm{Re}_n{}^2 + \mathrm{Im}_n{}^2} \qquad \psi_n = a\tan\left(\frac{\mathrm{Im}_n}{\mathrm{Re}_n}\right)\times\frac{360}{2\pi}$$

Here, ψ_n is the calculated phase angle relative to the local standard time, it is adjusted into local solar time in the calculation here. C_n is the amplitude of the diurnal variation.

The diurnal component of surface pressure is contributed by both the local diurnal mesoscale signal and global atmospheric tide. The diurnal atmospheric tide is mainly generated by the upper-atmospheric thermal forcing and this part of the surface pressure signal moves westward as the same speed as that of the Sun, with a diurnal surface pressure phase around 105 degree and amplitude about 20 Pascal in mid-latitude in Northern Hampshire (Chapman and Lindzen, 1970). Local diurnal mesoscale disturbance is generated by inhomogeneous heating caused by topography and has a local character. In the valleys, compared with the diurnal atmospheric tide, the local boundary layer heating effects are dominant.

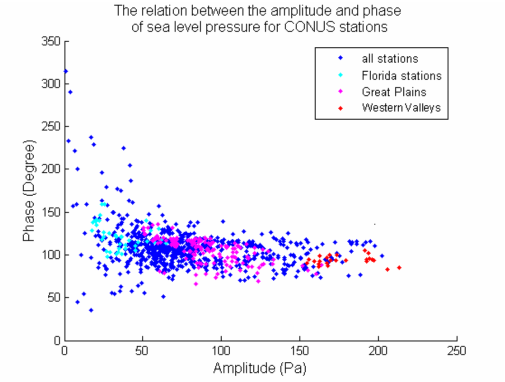

Figure 1: The distributions of the amplitude and the phase of sea level pressure variations for CONUS stations. The red ones represent stations from the valleys in western US.

3. Observations:

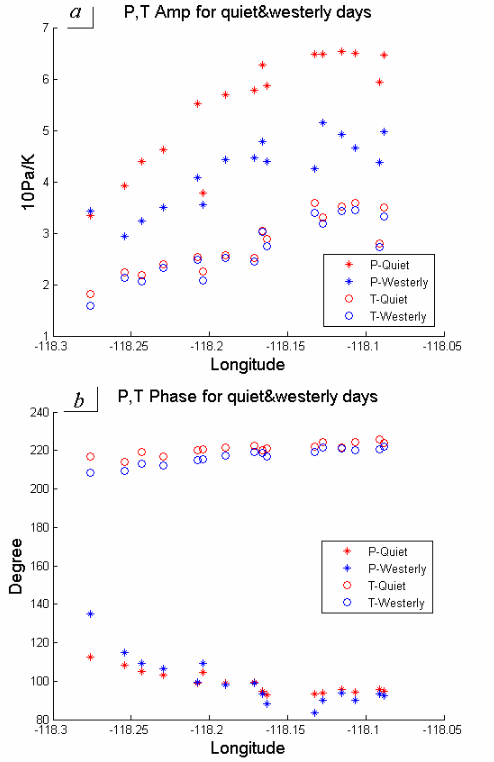

Figure 2: The a) amplitude and b) phase of the diurnal surface pressure/temperature perturbations for stations in Owens Valley during quiescent/westerly days.

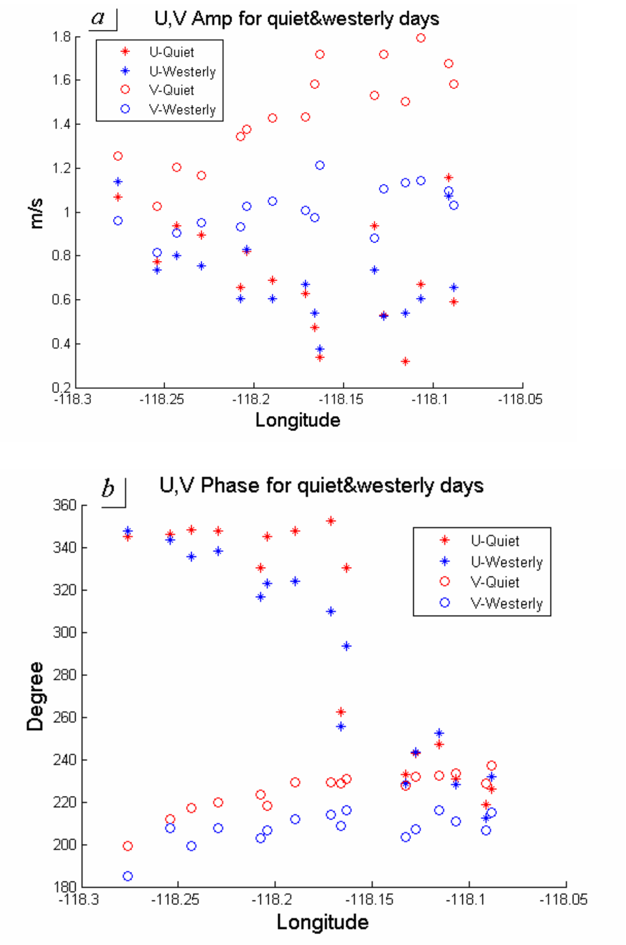

Figure 3: Similar to figure 2, but for the a) amplitude and b) phase of the surface observations of along-valley wind vector (U) and across-valley wind vector(V) during quiescent/westerly days.

In our preliminary analysis, the days are categorized according to the directions of the ridge top winds (soundings from Oakland and Reno). If the 700mb westerly wind exceeds 10m/s in 00Z sounding, that day will be classified as westerly days.

From figure 2, it can be seen that the amplitude (Figure 2a) and phase (Figure 2b) of the surface temperature are not very different for quiescent days or days with strong westerly. The phase is around 210 degree, which means the surface temperature reaches its maximum around 2pm. This result is reasonable since the sensible heating transported from ground to the air above it also reaches its peak at that time. However, the phase of the surface pressure is about 90 degree, which means that surface pressure researches its minimum before sunset (6PM). This could be easily understand if we treat the surface pressure perturbation as the accumulation of the density perturbation caused by the heating along the whole vertical air column. Although the surface temperature might start to fall after 3PM, the slope wind still exist which could cause counter flow convergence at the height near mountain top and then descend adiabatically, still warms the upper part of the air column.

The 210 degree phase of the along-valley wind vector (Figure 3b) means that up-valley wind reaches its peak around early afternoon, and down-valley wind dominates at night. The simultaneous phase between the surface along-valley wind and surface temperature may be explained by the small TAF (topographic amplification factor) in Owens Valley (Whiteman, 1990). The same amount of heating will cause more pressure drop in the valley than that of the plain near the valley mouth, and this pressure gradient will trigger the up-valley wind and the strength of which is determined by how much the difference is. As in Figure 2a and 3a, the westerly days have smaller diurnal surface pressure variation; they also have smaller surface along-valley wind than those quiescent days.

Figure 3b shows that the phase of the cross-valley wind vector is almost out of phase for stations on west/east slope. Station 1 on the western slope (the most western one) has the latest phase angle (350 degree). This shows that the up-valley wind starts from the valley bottom, and then builds up along the slope.

With the existence of synoptic wind at mountain top level, the amplitude and phase of the surface p, T, u and v are changed; especially surface pressure, any mass perturbation at high level can cause observable perturbation on surface pressure, even without affecting surface temperature. If the surface pressure acts as the integral of the whole column which is a function of the vertical temperature profile, the surface temperature is more like a boundary condition. The surface pressure perturbation could be a hint about what happened in the upper part of the valley because of the restriction of the observational data there.

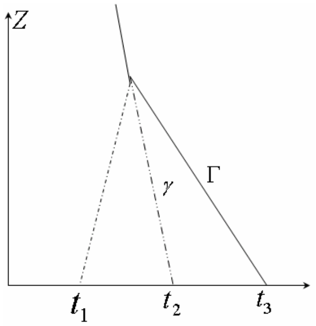

Figure 4: The sketch of the evolution of vertical temperature profile during the day.

Figure 4 shows the diurnal change of the vertical temperature profile. t_1 represents the stable boundary layer at night. t_2 is the vertical temperature profile in the morning or late afternoon. t_3 is the time when the mix layer reaches its maximum and the temperature lapse rate is adiabatic in the valley. With the existence of the inversion at some height near mountain top, the valley temperature change could only happen below the inversion level. When the incoming solar radiation heats the ground and warms up the boundary layer, the PBL depth keeps increasing till the temperature lapse rate is adiabatic, which means the atmosphere in the valley is well mixed and the potential temperature is the same. When solar heating is decreased or stopped, long wave radiation cooling dominates. The atmosphere in the valley becomes more and more stable, and the temperature lapse rate becomes larger.

The heat transfer through eddy diffusion does not happen instantaneously. There exist some lag between the time that the ground heated most and the time the air in the upper atmosphere heated most. This time lag is reflected in the phase difference between surface temperature and pressure. For example, in Figure 2b, the phase of the surface pressure is around 110 degree and the phase of the surface temperature is about 210 degree. This is equivalent to a four-hour difference for surface temperature reaches its peak and for surface pressure reaches its minimum. The time lag could be a way to test how the turbulence and scaled vertical motion work together to transfer surface heating upward effectively.

The amplitude of the diurnal surface pressure and temperature represents how much of the heating which reaches the ground during daytime could efficiently heat up the atmosphere in the valley, or in another way, the highest level that the mix layer could reach. Here, we try to estimate the depth of the mix layer by:

$$H = \frac{2\bar{T}}{\bar{\rho} g} \cdot \frac{|\hat{P}|}{|\hat{T}|} \qquad (1),$$

here, $|\hat{P}|$, $|\hat{T}|$ is the amplitude of the diurnal surface pressure and temperature variation. $\bar{\rho}$, $\bar{T}$ are the column averaged air density and temperature. It could also be an Index of the flushing effect caused by the strong mountain top wind, since $|\hat{T}|$ is mostly determined by the incoming solar radiation and is not very sensitive to the wind effect at the mountain top. But pressure amplitude is sensitive to the upper level wind. During quiescent days, the upward heat transport through eddy diffusion from the valley bottom, or though the adiabatic descending near mountain top, could build up a mix layer, which has almost the same potential temperature, that even reaches the mountain top. The intrusion of the mountain top wind into the valley, especially during daytime, will carry away and flush out the heat and prevent the effectivity of the mix layer buildup. Thus the mix layer could not reach the height of the mountain.

In order to test whether the estimated mix layer depth could be used to judge the intrusion of the mountain top wind into the valley, we calculate H (Eq. 1) for each day during T-Rex project period. Figure 5 shows the estimated daily mix layer depth H during T-Rex project, from Mar 24 to Apr 22, 2006.

Here, we think H=1500m could be a suitable criterion to distinct days with thick mix layer. Most of the days with relatively small H happen to be the IOP days during T-Rex project, since the IOP days are chosen according to the prediction of strong westerly flows over mountain top. For example, on Mar 26 and April 15-16, we have the strongest IOP events, with the intrusion of the mountain top westerly reached the ground. The quiet day with clear sky always has a large H, such as Mar 29 and Apr 18, which are also two EOP days, with clear sky during daytime and valley circulation dominates. The day with precipitation sometimes has weak surface temperature variation, the estimated H for that day may still be large though the surface pressure amplitude decreases, thus mashes the effectivity of H to distinct the intrusion of the mountain top westerly. March 25 and 28 are two wet IOPs , the calculated mix layer depth H are almost comparable to those quiet days, it's because the latent heating contributed by precipitation changes the vertical temperature profile.

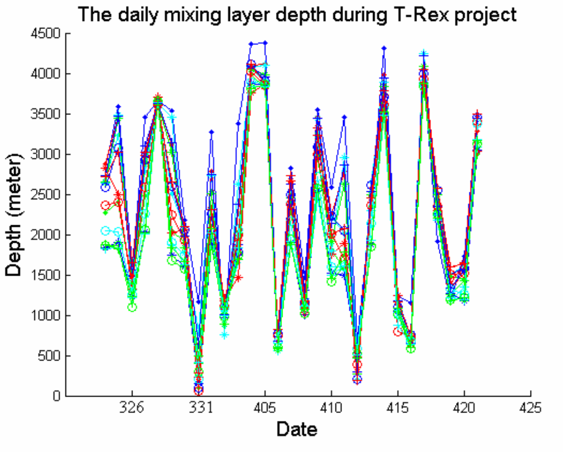

Fig 5: The daily estimated mix layer depth H for each DRI AWS station observations for days during Mar 24 and Apr 22, 2006.

4. Numerical simulations:

WRF 2d hill model is employed to do some idealized numerical simulations and to compare with observations. The effect of synoptic steering wind at mountain top is considered, to show how it modifies the mix layer and further changes the phase and amplitude distribution of surface pressure and temperature. The WRF simulation results will be given later.

5. Summary and Conclusions:

The amplitude and phase distributions of the diurnal component of surface temperature, pressure, cross-valley and along-valley wind vectors are calculated and categorized as quiet and westerly wind days according to the westerly at mountain top level. The amplitude and phase of surface temperature are similar for two classes while the pressure amplitude and phase differ markedly. On quiet days, the pressure phases are similar all across the Owens Valley. Generally, the diurnal component of surface pressure reaches its minimum around 6PM LST around sunset, while surface temperature reaches its maximum around 2:30pm LST when the sensible heat released by the ground reaches its peak. By contrast, on days with southwesterly wind, the phases show large differences across the valley, with the latest phase for stations on the western slope, and earliest phase for stations in the center of the valley. It shows that the slope winds always start the buildup from the bottom of the valley. Since the surface pressure is the integral of the column air mass above the surface, which, in turn, depends on the temperature distribution along the column, so there is a phase lag between surface temperature and pressure, which could be converted to the phase lag between the surface temperature and the column averaged temperature. This phase lag between surface pressure and temperature could also be treated as a function of the vertical turbulent mixing rate. The heating mixed-layer depth (H) is determined from the column averaged temperature and density and the ratio of pressure to temperature amplitudes, this ratio could also be an index of the flushing effect. During quiescent days, the turbulent well-mixed neutral layer develops to almost the ridge top. But during strong synoptic westerly wind days, the ridge top wind flushes out the valley. The mixed boundary layer becomes much thinner than that of the undisturbed days. The estimated H is less than 1500m for westerly days, and more than 2500m for undisturbed days. Also, the calculated mix layer depth or flushing index for each day during the T-Rex project shows that the day with low H falls into the days with strong mountain top westerly or IOPs. The high H days are always the quiet days except the raining days.

6. Acknowledgements:

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