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

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1. Introduction:

Diurnal solar heating is an important forcing for the Earth 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 property and terrain, inhomogeneous spatial heating generates mesoscale circulations with some local character, for example, plateau-plain circulation (Banta, 1984), mountain-valley circulation and sea-breeze.

The diurnal component of surface pressure is contributed by both the local diurnal mesoscale signal and global migrating atmospheric tide. The migrating 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 Hemisphere (Chapman and Lindzen, 1970). The local diurnal circulation generated by the local diurnal inhomogeneous heating has a surface pressure signal that moves with the gravity waves. In the valleys, compared with the diurnal atmospheric tide, the local boundary layer heating effects are dominant and the gravity waves are trapped locally.

In the mountain-valley area, the diurnal solar heating generates a typical diurnal valley circulation in clear undisturbed days. At night, a strong temperature inversion is present in the valley; the valley circulation is decoupled from the synoptic environment. In the morning, the incoming solar radiation generates upward heat transport through eddy diffusion from the valley bottom, combined with the adiabatic descent near ridge top, causes the convective boundary layer to grow and inversion layer to sink. In the afternoon, the valley atmosphere is well mixed. This well mixed convective layer may exceed the height of the ridge top. Now the valley atmosphere becomes coupled with the atmosphere above the valley by enhanced vertical transfer of momentum. After sunset, the sensible heat flux divergence causes cooling to start as a shallow layer above the slope, and then the compensatory rising motion in the valley center produces the cooling over the whole valley. (Whiteman, 1990)

2. Data analysis methods:

A convenient way to monitor and classify diurnal circulations is by isolating the diurnal component of the surface observations from the noisy observational data.

By doing a harmonic analysis, the diurnal component of the surface pressure can be separated with the expression of amplitude and phase (Mass et al, 1991).

$$\mathrm{Re}_n = \sum_{k=t_1}^{t_N} P_n(k)\cos\frac{2\pi k \times 24}{N}, \quad \mathrm{Im}_n = \sum_{k=t_1}^{t_N} P_n(k)\sin\frac{2\pi k \times 24}{N}$$

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

Here, $P_n(k)$ is the observed surface pressure value at time k for station n. ψ_n is the calculated phase angle for the diurnal component of $P_n(t)$. It is related to the local solar time (LST). C_n is the amplitude of the diurnal component for $P_n(t)$.

3. Observations:

3.1 Continental United States

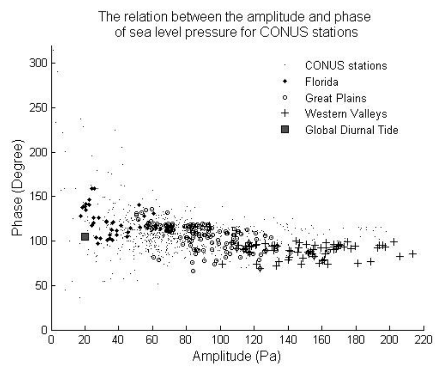

Figure 1: The distributions of the amplitude and the phase of the sea level pressure variations for CONUS stations for June, July and August, 2001-2004.

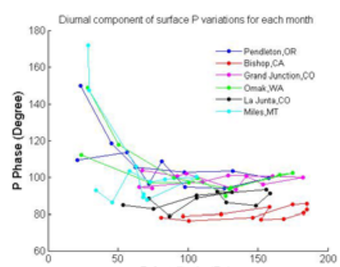

Figure 2: The amplitude and the phase of the surface pressure variations for each month of the year (2001-2004) for some valley stations.

Harmonic analysis has been applied to nearly 1000 ASOS over the CONUS. Their amplitude and the phase of the sea level pressure variations (Figure 1) for summer season show some interesting patterns: those stations from Florida peninsula have relatively small amplitudes and late phases, which could be the effect of sea breeze. Those stations from the Great Plains and Midwest show a “continental enhanced tide” pattern, which have phases similar to that of the global diurnal atmospheric tide but with much larger amplitudes. Those stations from dry western valleys have the largest amplitudes, more than 150 Pascal, and relatively early phases, around 90° (6AM in LST), such as station Bishop, Grand Junction and Rifle. The tide effect seems negligible for these valleys; perhaps because the local terrain effect is so strong. In Figure 2, the amplitude and the phase of the surface pressure variations for each month of the year for some valley stations are presented. In general, valley stations have relatively large amplitudes and early phases in warm season for their diurnal surface pressure variations, but much small amplitudes and late phases in winter time.

3.2 Owens Valley and DRI network

The unique properties of those valley stations drew our attention to the western valleys in the United States. The T-REX (Terrain Induced Rotor Experiment) project was held on March-April, 2006 in Owens Valley, CA (Grubisic et al., 2005). In association with the T-REX project, sixteen Automated Weather Stations were installed and maintained by the Desert Research Institute. Their fine spatial (distance between stations is around 3km) and temporal resolutions (30 Seconds) are very helpful for the study of the extreme diurnal surface pressure signals in Owens Valley, which is also a good representative of the particular dry valleys in the Western United States.

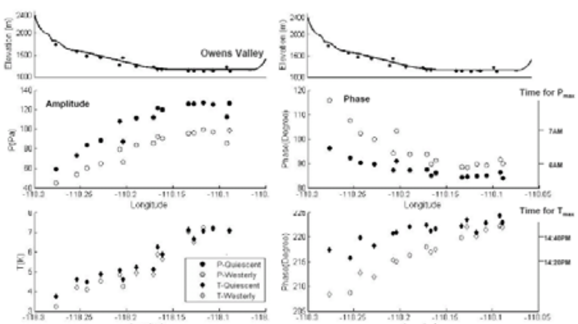

Figure 3: The amplitude (Left) and phase (Right) of the diurnal components of the surface pressure and temperature perturbations for stations across Owens Valley for quiescent and westerly days for March-April, 2006.

In our analysis, the days are categorized according to the directions of the ridge top winds (soundings from Oakland, Independence and Reno). If the 700mb westerly wind exceeds 10m/s in 00Z (4PM LST) sounding, that day will be classified as westerly days. For the whole T-REX project, from March 1 to Apr 30, 2006, we have 32 days for quiescent days and 29 days for westerly days.
The amplitude and phase of the surface pressure and temperature are presented in Figure 3. The temperature phases are around 220 degree, which means that the diurnal component of surface temperature variations reaches its maximum around 2:40PM LST. This time can be explained as the time that surface sensible heat transported from ground to the air above it also reaches its peak. As to the diurnal components of the surface pressure variations, their phases are around 90 degree, which means that the diurnal components of surface pressure research their minimum around sunset time (6PM). This kind of diurnal amplitude and phase distribution should be able to be explained by the diurnal valley circulation.

Ridge top wind has more effects on surface pressure. Figure 3 shows that temperature amplitudes are not quite different for westerly or quiescent days. But the amplitudes of surface pressure decrease about 20Pa for westerly days.

3.3 Mixing layer depth

Valley atmosphere satisfies the hydrostatic law, that is surface pressure approximates the integral of the column air mass above the ground and is a function of the vertical temperature profile. Then the diurnal surface pressure variation is the summation of the diurnal temperature variations along the air column till some common pressure surface if we assume the diurnal change of pressure above that level is negligible.

The existence of synoptic wind near ridge top level will modify the diurnal valley circulation. Especially surface pressure, any mass perturbation at high level will cause observable perturbation on surface pressure, even with only little effect to the surface temperature.

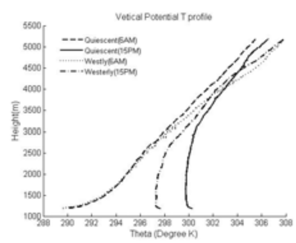

Figure 4: Averaged vertical potential temperature profile for Quiescent/Westerly days for 6AM/3PM in Owens Valley for T-Rex period (Derived from University of Leeds Independence Airport Rawinsonde Data).

Figure 4 is the averaged potential temperature profile derived from University of Leeds Independence Airport 60 days Rawinsonde Data for the T-REX period. The vertical potential temperature profile shows that the temperature lapse rate is almost adiabatic in the afternoon below the ridgetop. At night, a shallow layer with strong inversion forms near the ground. The potential temperature profile shows that for quiescent days, the mixed layer in Owens valley is about 3000m, near the top of the valley. But for westerly days, the top of the mixed layer is around 2500m.

To estimate the mixed layer depth in terms of the diurnal surface observations, we include two assumptions here. One is that the diurnal temperature and pressure variations are negligible above the top of the mixed layer. For deep valleys, with the existence of the inversion at some height near ridge top, the valley temperature change could mainly happen below the inversion level. The other assumption is that although the nighttime inversion contributes a lot to the diurnal surface temperature variation, it does not affect much to the surface pressure because it is just a thin layer. That’s why we ignore it in the schematic plot of the diurnal vertical temperature profile variations in Figure 5. In Figure 5, the strong inversion at time t_1 refers to the stable boundary layer at night. After sunrise, the incoming solar radiation heats the ground and the inversion breaks up, the PBL depth keeps increasing.

t_2 is the vertical temperature profile in the morning (or evening) transition time, with a standard lapse rate. In the afternoon, at time t_3, the temperature lapse rate becomes adiabatic, the valley atmosphere is well mixed and potential temperature becomes the same for the whole valley, the vertical temperature lapse rate becomes adiabatic. After sunset, solar insolation ends, long wave radiation cooling dominates. The atmosphere in the valley becomes more and more stable, and the temperature lapse rate becomes larger and finally back to that of t_1.

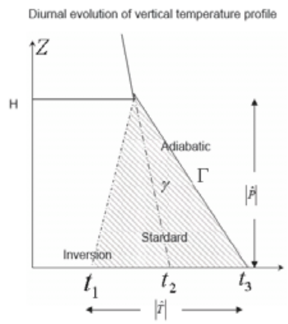

Figure 5: Schematic plot of the diurnal evolution of the vertical temperature profile. t_1 represents the night time when inversion reaches its maximum in the valley; t_2 represents the morning/evening transition time; t_3 represents the afternoon time when the valley atmosphere is well mixed; H is the mixing layer depth.

The relative amplitude of the diurnal surface pressure versus 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 mixing layer could reach. In Figure 5, the triangle shadow area is the diurnal changes of the temperature that will contribute to the diurnal surface pressure change; the lower boundary of the triangle is diurnal surface temperature change.

The pressure perturbation for a thin layer dz is $dP = dzd\rho g \approx dz\rho gdT/T$. Integrating from ground $z = 0$ to the top of the mixed layer $z = H$, we'll get the diurnal pressure variation at ground $\Delta p \approx H\bar{\rho}\Delta T/(2\bar{T})$. Then, a simple estimation of the mixed layer depth could be:

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

In Equation (1), $|\hat{P}|$, $|\hat{T}|$ are the amplitudes of the diurnal surface pressure and temperature components. In the real calculation, we use equivalent diurnal temperature amplitude instead because the formula we derived here to estimate the mixed layer depth ignores the nighttime shallow strong inversion layer near the ground. The shallow inversion layer is more obvious for deep valleys, which have the potential for cold pool to develop. For Owens valley, the equivalent diurnal temperature amplitude is about 80% of the total diurnal temperature amplitude. $\bar{\rho}$, $\bar{T}$ are the column averaged air density and temperature. Their ratio could be replaced by the ground value of $\bar{T}/\bar{\rho}$.

The defined mixing depth here can be used as an index to show the flushing effect caused by the ridge top wind, since $|\hat{T}|$ is mainly determined by the incoming solar radiation and is not very sensitive to the wind effect at the ridge top. But pressure amplitude is sensitive to the upper level changes. The intrusion of the ridge top wind into the valley, especially during daytime, will destroy the adiabatic descent mechanism, flush out and carry away the heat and prevent the buildup of the mixed layer. Thus the mixed layer may not be able to reach the ridge top height for the days with strong synoptic wind.

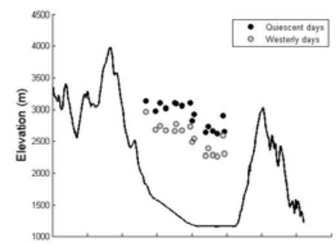

Figure 6: The estimated daytime maximum mixed layer depth for 16 DRI AWS in Owens Valley for T-REX project period from Mar 1 to Apr 30, 2006.

In order to test whether our formula of H could be used to estimate the real mixed layer depth in the valley and predict the intrusion of the mountain top wind into the valley, we calculated H for each station in Owens Valley according to two categories: quiescent and westerly days, for the whole T-REX period. Figure 6 shows the results. For quiescent days, the daytime maximum mixed layer reaches almost ridge top level; for westerly days, the mixed layer height is about 500 meters below, which is consistent with the mixed layer heights derived from the averaged sounding data shown in Figure 4.

There are two mechanisms that transport the ground sensible heat to the valley atmosphere: turbulence near the valley bottom and adiabatic descent in the valley center. (De Wekker et al, 1998). The heat transfer through eddy diffusion from the ground and adiabatic descent do not warm up the valley atmosphere instantaneously. There exist some lag between the time that the ground gets heated most and the time that the air in the upper part of the valley gets heated most. This time lag is reflected by the phase difference between surface temperature and pressure. In Owens Valley, the phase of the surface pressure is around 90 degree (6:00AM LST) and the phase of the surface temperature is about 220 degree (2:40PM LST) in spring. This is equivalent to a three-hour time lag for ground temperature to reach its peak and for surface pressure to reach its minimum.

4. Numerical simulations:

4.1 The set up of WRF 2d idealize simulations:

WRF hill_2d model is employed to do the idealized numerical simulations of the diurnal valley circulation and to explain some of the observation results. The simulations presented here are 2 dimensional, with an idealized valley between two bell shaped mountains.

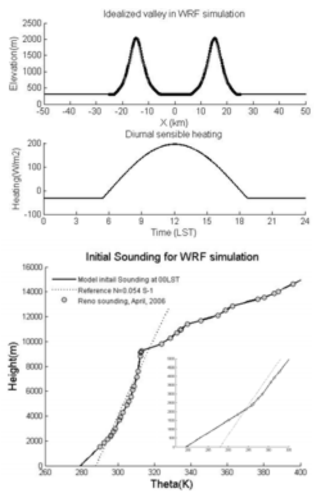

Figure 7: UP: Terrain used in idealized WRF 2d simulation (Solid line), with heating applied to the region between -25km and 25km (Dotted area); Middle: The diurnal sensible heating used in the WRF idealized simulation; Lower: The initial sounding of the simulation.

The computational domain of the simulations is 100km in x direction (across valley) with spatial resolution 250m. The domain extends to 16km in the vertical direction and is covered by 200 equally spaced grid points starting from the ground. The time step adopted is 6s for the advection terms with a 0.6s time step to compute the acoustic modes. A third-order-accurate Runge-Kutta scheme is used for the time integration, and third-and fifth-order-accurate spatial discretization schemes are used for the vertical and horizontal advection schemes, respectively. At the lateral boundary of the domain, the open boundary condition is chosen for x direction and periodic condition is chosen for y direction to represent an infinite long valley. At the upper domain boundary, a rigid lid (w=0) is employed to 16km with a 5km Rayleigh Damping layer near the top. For the whole domain, 1.5 order TKE closure sub-grid model is chosen to parameterize the unresolved Reynolds stresses in terms of resolved quantities. In order to simulate the diurnal solar radiation, a simple heating is applied along $z = h(x)$ for x between -25km to 25km (Figure 7), which include the area of the two mountains and the valley. A larger heating region does not change the result much but needs much larger outer domain for computational stability. The surface sensible heating has a sinusoidal shape during the day to represent the incoming shortwave radiation and nearly constant at night to represent the outgoing long wave radiation as in Figure 7, with $Q_{\mathbf{max}}$ = 192 Wm^{-2} at noon, and $Q_{\mathbf{min}}$ = -32 Wm^{-2} at midnight. The model is integrated for 2 days, and the first 24 hours are used as a spin-up for the whole system. The diurnal circulation of the second day is used as the representative of the diurnal valley circulation pattern. The initial sounding is derived from an averaged 4AM sounding from Reno in April, 2006 (Figure 7) with a smooth vertical temperature profile and no water vapor. The simulation of the diurnal valley circulation under quiescent condition is assumed that the background atmosphere is motionless (U=V=W=0).

4.2 Diurnal valley circulation and energy budget analysis:

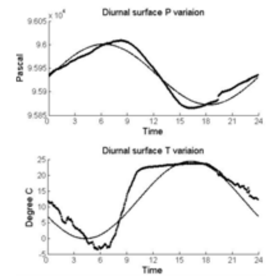

Figure 8: Diurnal surface pressure and temperature variations at the valley center (x=0) with their diurnal component.

The diurnal surface pressure and temperature variations at the valley center ($x = 0$) are shown in Figure 8 with its diurnal component. The results show that the phase for diurnal surface pressure component is 90 Degree, which refers to 6PM for diurnal surface pressure to reach its minimum. The phase for diurnal surface temperature component is 245 Degree, which refers to 4:20PM for diurnal surface temperature to reach its maximum. Although the phases calculated from the observation and idealized WRF simulation are different, but the existence of time lag between surface pressure minimum and surface temperature maximum are consistent.

The thermodynamic energy budget in the valley is calculated to study the heating mechanisms in the valley.

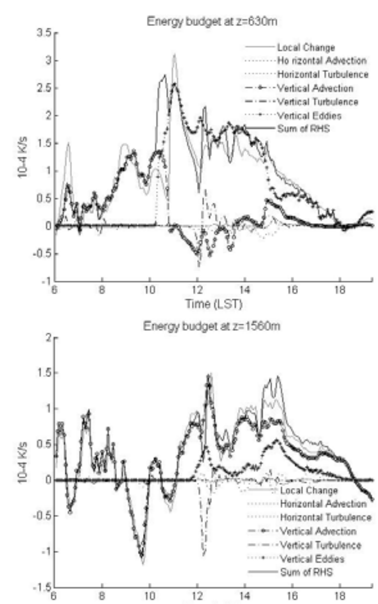

Figure 9: The daily heating budget at the valley center near ground z=630m and at upper part of the valley z=1560m for the idealized 2d WRF simulation.

Figure 9 shows the daily energy budget at the valley center near ground (z=630m) and in the upper part of the valley (z=1560m). Near the ground, the local air temperature is controlled by the residue part of the incoming sensible heat and eddy heat transportation; the net sensible heat becomes positive after sunrise and changes sign about 2 hours before sunset. Although the incoming sensible heating $\dot{Q}$ is still positive in the late afternoon, the heat lost by the unresolved eddy and horizontal and vertical resolved eddies is more than the heat gained by the solar radiation. In the upper part of the valley, the air starts to be warmed up after 11AM, and ends around 7PM. The heating at the upper part of the valley is mainly contributed by the vertical adiabatic descent. In the late afternoon, although the surface temperature already starts to fall, but the adiabatic descent in the upper part of the valley still warms up the atmosphere there, thus surface pressure keeps decreasing until after sunset.

Using diurnal surface pressure and temperature amplitude from Figure 8, the mixed layer depth of the WRF simulated valley circulation under quiescent condition is derived, with H=2000 for quiescent days, which is almost the ridgetop level and the result is similar to the mixing depth get from the vertical potential temperature profile.

4.3. The generation of plain-valley wind:

A series of WRF idealized diurnal simulations with fixed Q_{max}=192W/m2 but modified valley depth have been done. The results are presented in Figure 10.

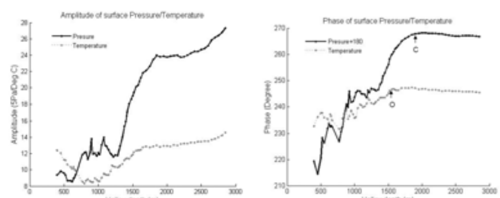

Figure 10: The amplitude/phase of the diurnal surface pressure/temperature at the valley center (X=0) for different valley depth.

For valleys deeper than 2km, the surface pressure and temperature phases will no longer change with the valley depth. That's because the daily maximum mixing layer depth for heating strength Q_{max}=192W/m2 is about 2km. So the valley mixed layer is always below the ridgetop during the day. The 90 degree for surface pressure phase and 245 degree for surface temperature phase are typical for pure diurnal valley circulation. As we decrease the valley depth, the surface pressure amplitude and phase will start to change first. The detailed study shows that the pressure phase becomes earlier and amplitude becomes smaller once the plain-valley wind built up. Surface temperature phase and amplitude will start to change only if the front of the plain-valley wind and the valley upslope wind reaches the valley bottom. If the daily mixing layer is higher than the surrounding mountain, then the valley circulation is no longer confined in the valley, the pressure gradient between the surrounding environment and the valley will cause a broad scale valley-plain circulation to build up, which will then destroy the well-defined valley circulation. If the valley depth is lower than the potential mixing layer depth, then the generated mixing layer will not reach its potential height, instead it'll be a little bit higher than the ridgetop, with surface pressure and temperature phases differ from those of the pure valley circulation. Also, the continental diurnal atmospheric tide may no longer be negligible because the valley atmosphere is now connected to the environment.

In our analysis here, whether the plain-valley wind will be generated is mainly determined by the relative height of the surrounding mountain and the estimated daily maximum mixing layer depth inside the valley. But when the plain-valley wind will be generated is controlled by the pressure and temperature gradient between the valley atmosphere and the surrounding environment. (De Wekker et al, 1998; Kimura and Kuwagata, 1993)

4.4. The seasonal character of the diurnal valley circulation:

A series WRF idealized simulation with fixed valley depth (2000m) but modified incoming sensible heating strength have been done to simulate the seasonal character of the diurnal valley circulation. The results are presented in Figure 11.

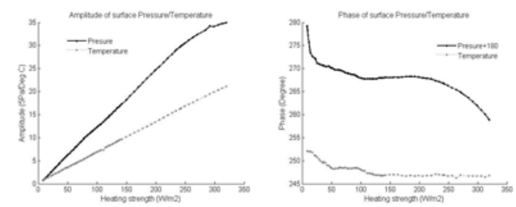

Figure 11: The amplitude/phase of the diurnal surface pressure/temperature at the valley center (X=0) for different heating strength.

When we increase the sensible heating strength, the amplitudes of both surface pressure and temperature will keep increasing till the heating strength reaches some critical value. If the sensible heating generated daily mixing layer is higher than the surrounding mountain, then the valley-plain circulation will be built up, which will then destroy the well-defined valley circulation. So the increasing rate of the pressure amplitude becomes less than that of the temperature for strong sensible heating, also the pressure phase becomes earlier. That's why in the summertime, some shallow valleys have surface pressure phases less than 90 Degree. When we decrease the sensible heating strength till below some threshold value, both pressure and temperature phases will become later. These are similar to the winter time valley. The weak solar insolation in the morning fails to generate strong upslope wind and the mixing layer it generated is quite shallow, the dominant heating mechanism in the valley is turbulent heat transport from the ground. Also the upslope wind will not change sign right after sunset. Both morning breakup and evening transition are delayed. So both surface pressure and temperature phases become later in winter time.

5. Conclusions:

The amplitude and phase distributions of the diurnal component of surface temperature and pressure are calculated and categorized as quiescent and westerly days according to the ridge top westerly. The amplitude and phase of surface temperature are similar for two classes while the pressure amplitude and phase differ markedly. 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. 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 explained by the time lag of the ground sensible heating and scaled valley circulation. The mixing layer depth H is determined by the column averaged temperature, density, and the ratio of pressure to temperature amplitudes. This ratio could also be used as an index of the flushing effect of the ridge top wind. During quiescent days, the turbulent well-mixed neutral layer can develop to almost the height of the ridge top. But during strong synoptic westerly wind days, the ridge top wind flushes out the valley thus carries away part of the heating transported from the ground. The mixing boundary layer becomes much thinner than that of the undisturbed days. In Owens Valley for the whole T-Rex period, the estimated H reaches the ridgetop for undisturbed days, but is about 500m lower for westerly days.

WRF 2 dimensional simulations have been applied to study the diurnal valley circulation. The simulated diurnal component of the surface temperate variation reaches its maximum around 4:20PM, and the simulated diurnal component of the surface pressure variation reaches its minimum at 6PM, which is about 1 hour and 40 minutes later. The energy budget analysis shows that the diurnal surface temperature variation is dominated by the incoming sensible heating and the eddy heat transport. The diurnal surface pressure variation is the cumulative effect of the temperate changes from the ground to the ridgetop, the dominant factor is the vertical heat advection. In the late afternoon, although the temperature at and near the ground start to decrease, the adiabatic descent in the upper part of the valley still warms up the atmosphere there, thus the surface pressure keeps decreasing until after sunset.

By fixing the incoming sensible strength but modifying the mountain height, a general picture about how diurnal surface pressure and temperature respond to different valley depth is generated. The results show that with fixed heating strength, the simulated surface pressure and temperature phases become earlier and earlier as we decrease the mountain height. The explanation to these early phases is by the intrusion of the plain-valley wind, which can destroy the well-defined valley circulation in late afternoon when the mixed layer depth exceeds the mountain height. If the potential mixed layer depth could be above the mountain height, the pressure gradient between the valley and the surrounding environment will generate a broad scale valley-plain circulation. If mixed layer top is below mountain height, the valley will become a confined system and isolated from the environment.

By fixing the mountain height but modifying the incoming sensible heating strength, the seasonal character of the surface pressure and temperature phases for deep valleys has been simulated. The results show that the phases are later in wintertime than in summertime. Also, the time lag between surface pressure minimum and surface temperature maximum becomes longer as we decrease the ground sensible heating strength. The energy budget analysis gives the explanation by different valley heating mechanisms. In summertime, the strong solar insolation generates valley circulation with deep mixed layer. In wintertime, solar insolation is small, it fails to generate a strong upslope wind and the mixed layer it generated is quite shallow. The dominant heating mechanism for valley atmosphere is turbulent heating in the lower part of the valley. Both morning breakup and evening transition are delayed because of the weak daytime shortwave radiation and nighttime longwave cooling. Thus the phases of surface pressure and temperature become later, also the time lag between surface temperature maximum and pressure minimum becomes longer.

6. Acknowledgements:

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