Evaluating Spatial Scales of Eddy Covariance Fluxes over the Southeast U.S. using 20 Hz Wind and Temperature Data from the NASA DC-8 Meteorological Measurement System

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Introduction

Accurate calculation of eddy covariance fluxes of chemical constituents requires precise determination of turbulent scales of motion. During the 2013 SEAC⁴RS (Studies of Emissions and Atmospheric Composition, Clouds, and Climate Coupling by Regional Surveys) mission, fast-response, in-situ measurements of static pressure, static temperature (T), three-dimensional winds (U, V, W), Formaldehyde (CH_2O) and Isoprene (C_5H_8) were collected on board the NASA DC-8. In the boundary layer above dense oak-pine forests of the southeastern United States, strong updrafts detected by the Meteorological Measurement System (MMS) correlated with peak concentrations of CH_2O and/or C_5H_8 in regions of active vertical mixing.

Isoprene is a volatile organic compound which, in the presence of nitrogen oxides, is converted to Formaldehyde and other products. Vertical fluxes of these chemical constituents critically depend on dynamic mixing scales which separate active turbulence from mesoscale motions. In this study, Cospectra of 20Hz wind and potential temperature ("Theta") data from the MMS are computed in order to define scales relevant for vertical transport within the mixed layer above forest canopies. Vertical fluxes of sensible heat and momentum are calculated from the MMS data in regions of chemical enhancements. Dynamic fluxes are compared for two DC-8 flights: 20130821, during a pass over central Mississippi, and 20130906, when the aircraft flew vertically stacked legs over the Isoprene volcano of southeast Missouri.

Flux Methodology: 20130821 Flight

On 20130821 between 15:28 and 15:56 UT, the DC-8 descended first to 1140m, and then to 850m, while flying east over Mississippi. Enhanced CH_2O concentrations were observed at to, and then flew northeast for a time at the lower altitude. Figure 1 shows a positive correlation between 20 Hz MMS W and the 10 Hz CH_2O observations. To determine active flux scales, the mean and trend were removed from MMS data, and U-W, V-W and W-Theta Cospectra were computed for the entire flight leg. The V-W Cospectrum (Figure 2) shows a broad region of (mostly) negative correlation. The corresponding Ogive (Figure 3) shows cumulative Cospectral power. Similar to the U-W and W-Theta Ogives, the slope of the Ogive with frequency sharply asymptotes to zero at 0.01 Hz. Although some Cospectral power can be found at longer scales, it is likely driven by mesoscale processes (e.g., gravity wave dynamics) rather than turbulence.
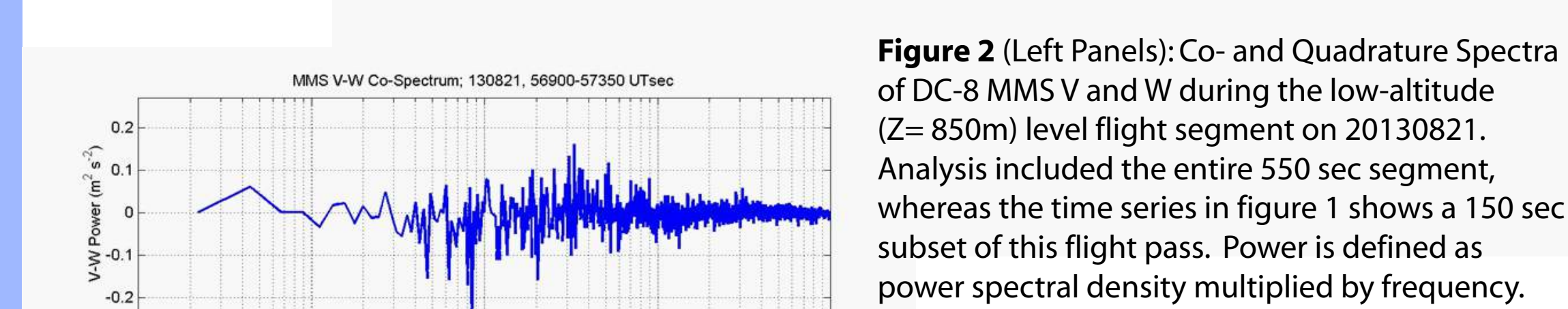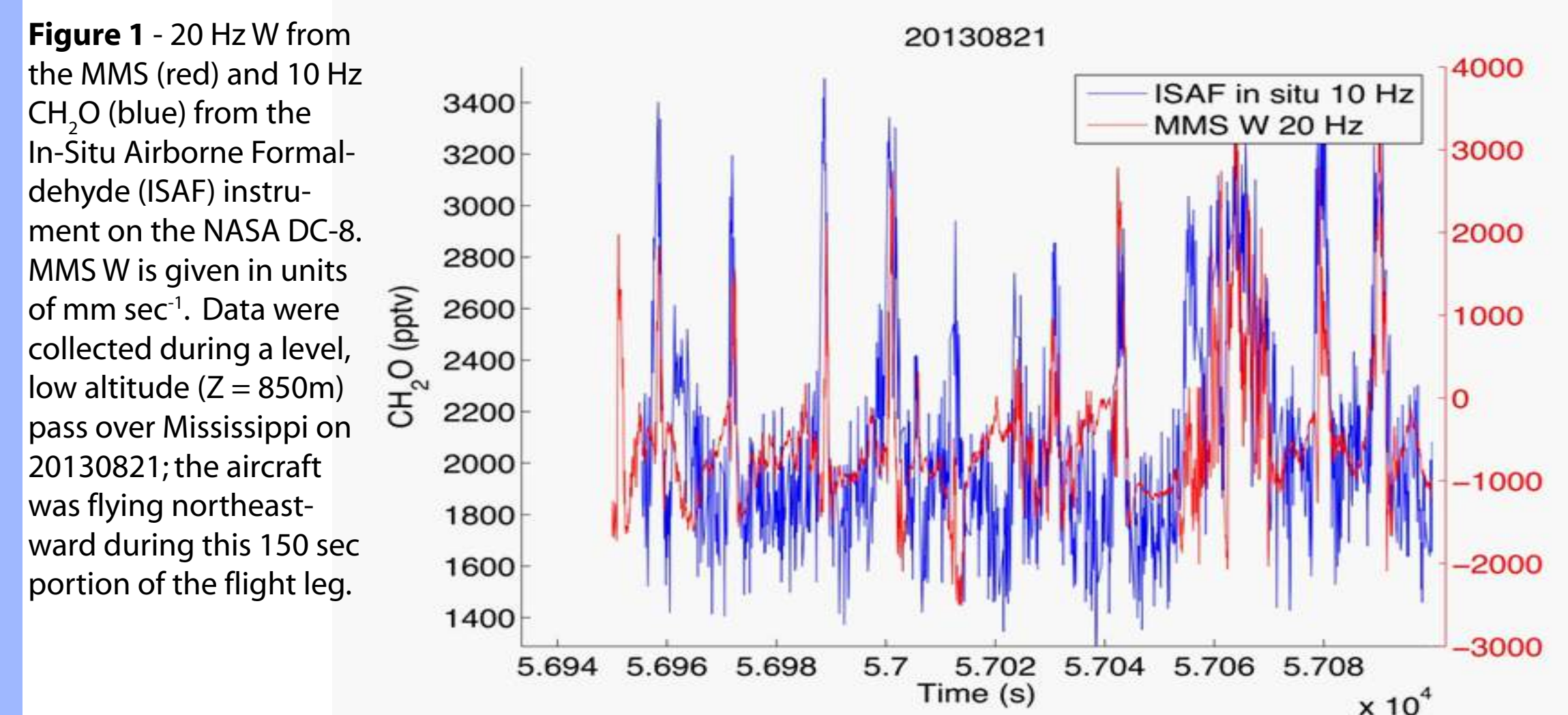
Figure 1 - 20 Hz W from the MMS (red) and 10 Hz CH_2O (blue) from the In-Situ Airborne Formaldehyde (ISAF) instrument on the NASA DC-8. MMS W is given in units of mm sec⁻¹. Data were collected during a level, low altitude (Z = 850m) pass on 20130821; the aircraft was flying northeastward during this 150 sec portion of the flight leg.

Figure 2 (Left Panels): Co- and Quadrature Spectra of DC-8 MMS V and W during the low-altitude (Z= 850m) level flight segment on 20130821. Analysis included the entire 550 sec segment, whereas the time series in figure 1 shows a 150 sec subset of this flight pass. Power is defined as power spectral density multiplied by frequency.
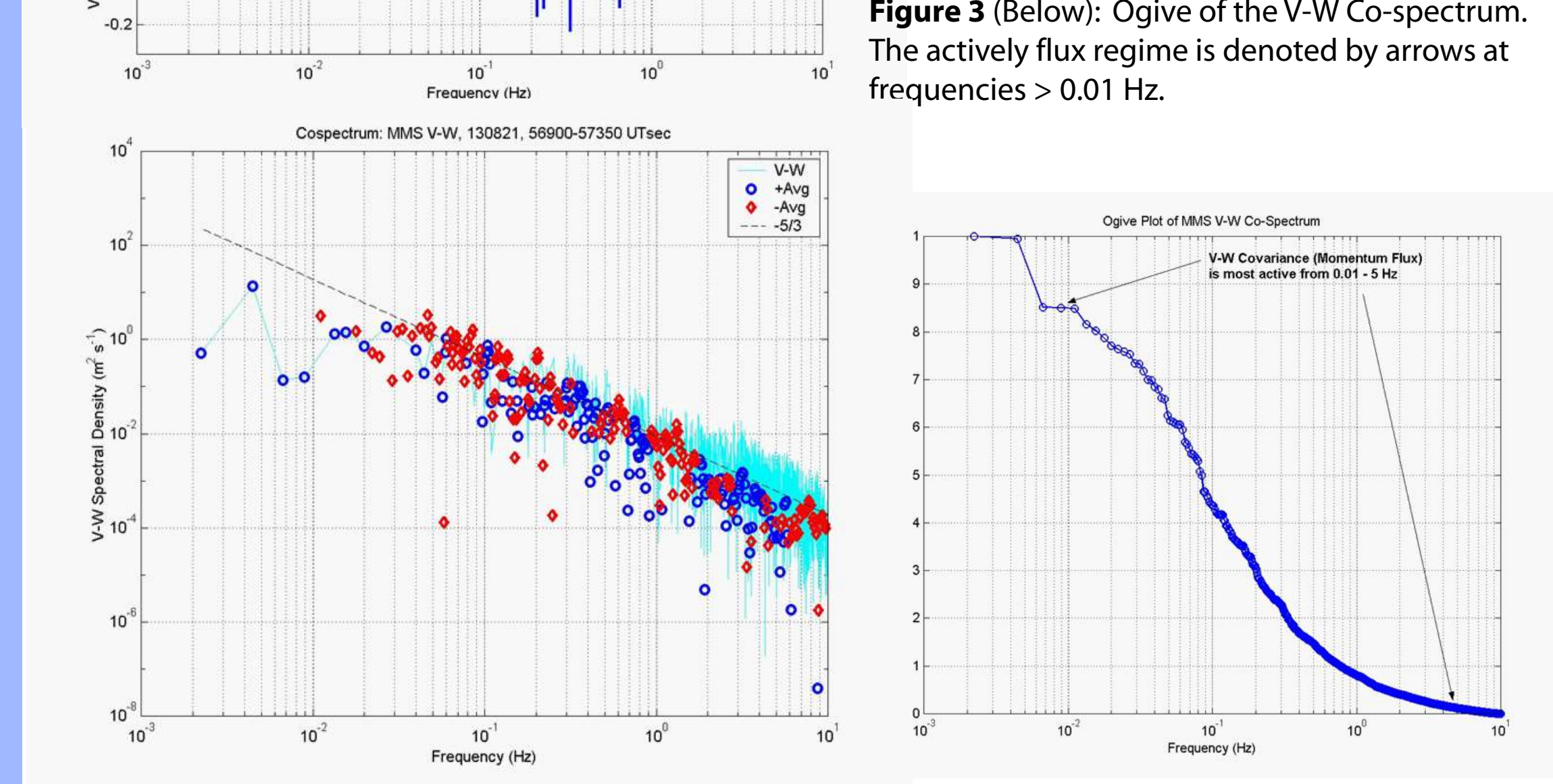
(Lower left panel): V-W Quad-Spectrum displayed as a power spectral density; colored points are locally windowed averages with blue (red) indicating positive (negative) correlations at the mean frequency of each overlapping window.

Figure 3 (Below): Ogive of the V-W Co-spectrum. The actively flux regime is denoted by arrows at frequencies > 0.01 Hz.

Given the lower frequency bound of 0.01 Hz for this flight leg, MMS U, V, W, and Theta measurements were center-averaged across a 100-sec interval to determine time-dependent local means. Since the Cospectral densities follow a -5/3 power law (indicative of turbulent energy transfer) out to the Nyquist frequency, the dynamically driven perturbations (U', V', W' and Theta') were computed without filtering the smaller scales. Utilizing potential temperature in lieu of temperature reduces artifacts due to small changes in aircraft altitude, and is sufficiently accurate (<5% error) in the planetary boundary layer (PBL) where T and Theta perturbations are nearly equal.

Figure 4 shows the original and averaged MMS time series. The black box over the vertical winds denotes the region of CH_2O enhancement from Figure 1. The eddy correlation method was applied to compute vertical fluxes of sensible heat (H) and momentum (tau) using:

$$\tau_{xz} = -\rho \overline{u'w'}$$

$$\tau_{yz} = -\rho \overline{v'w'}$$

$$H = \rho C_p \overline{w'\theta'}$$

Figure 5 shows all three fluxes. Along this flight leg, the chemically active region shows positive momentum fluxes (given positive wind shear, momentum transfer to this level from faster winds aloft) as well as negative sensible heat flux.
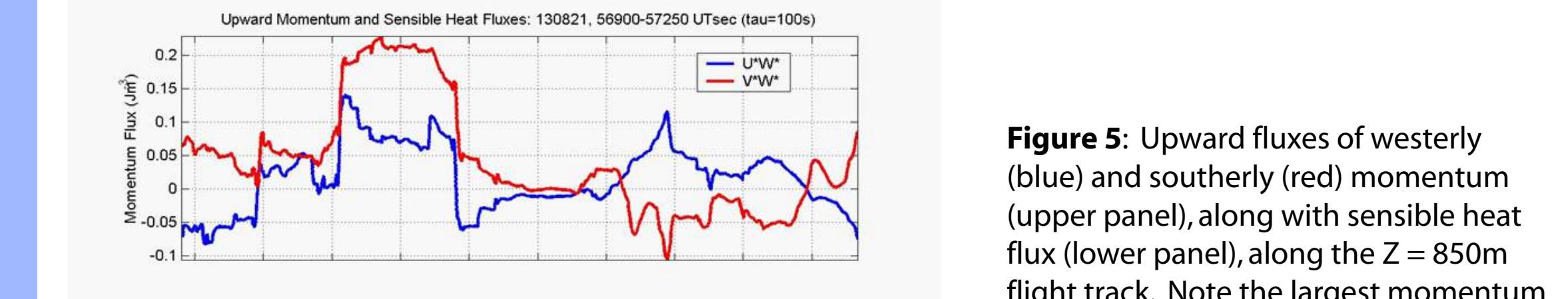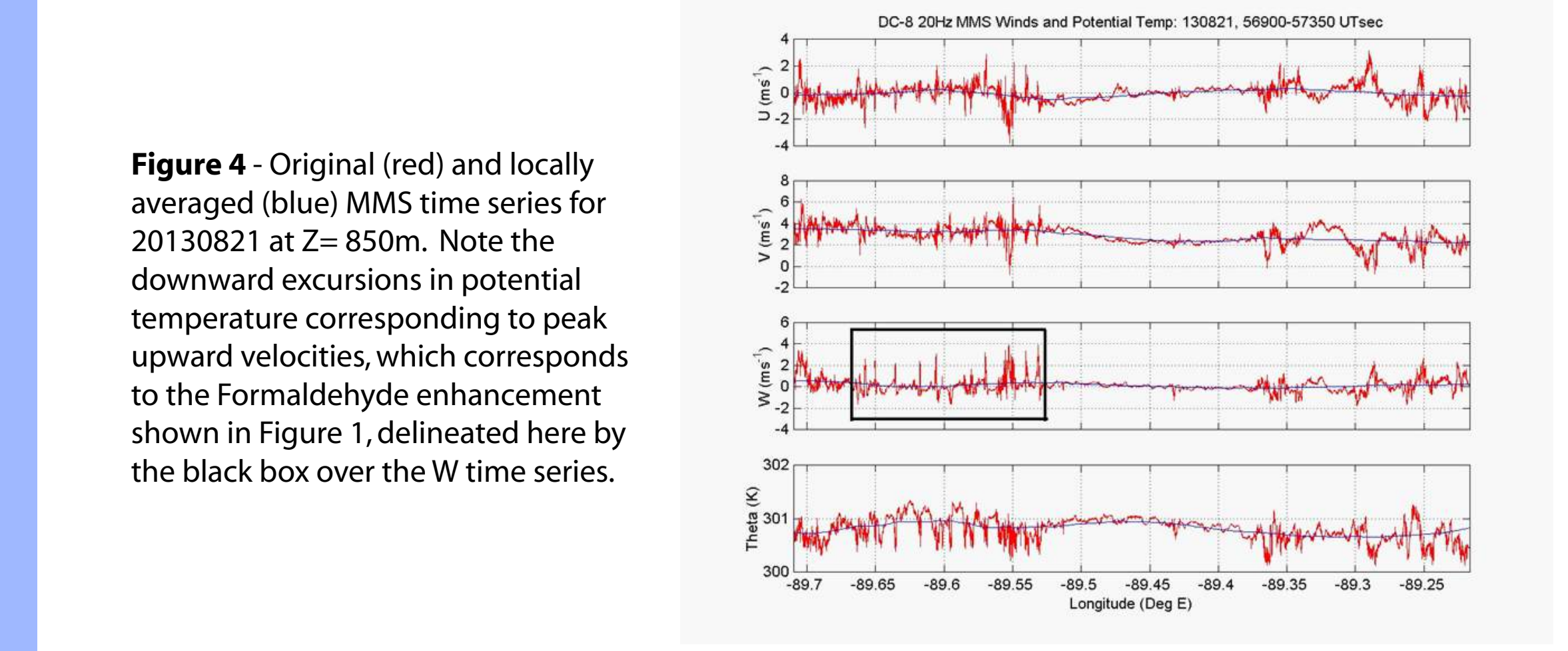
Figure 4 - Original (red) and locally averaged (blue) MMS time series for 20130821 at Z= 850m. Note the downward excursions in potential temperature corresponding to peak upward velocities, which corresponds to the Formaldehyde enhancement shown in Figure 1, delineated here by the black box over the W time series.

Figure 5: Upward fluxes of westerly (blue) and southerly (red) momentum (upper panel), along with sensible heat flux (lower panel), and the Z = 850m flight track. Note the largest momentum fluxes are observed within the region of Formaldehyde enhancement. (see Figure 4 caption for explanation).

Sensitivity to Averaging Scale

Figure 6 shows dynamic fluxes for the upper (Z = 1140m) flight leg on 20130821. Based on the Cospectra (not shown), the same 100-second averaging interval was used for the calculations (solid lines). At this level, strong momentum and heat fluxes appear near 90.7W longitude. The computations were repeated using averaging intervals that were either shortened or lengthened by a factor of two, resulting in large, unrealistic changes in flux.

In the region of interest, shortening the averaging interval results in narrow bands of flux having overestimated magnitudes. Conversely, lengthening the averaging interval results in broad bands of flux having diluted features. The accuracy of calculations that depend on fluxes (such as vertical flux divergence) necessarily relies upon reliable and consistent calculation of mean fluxes within these regions of turbulent transport.
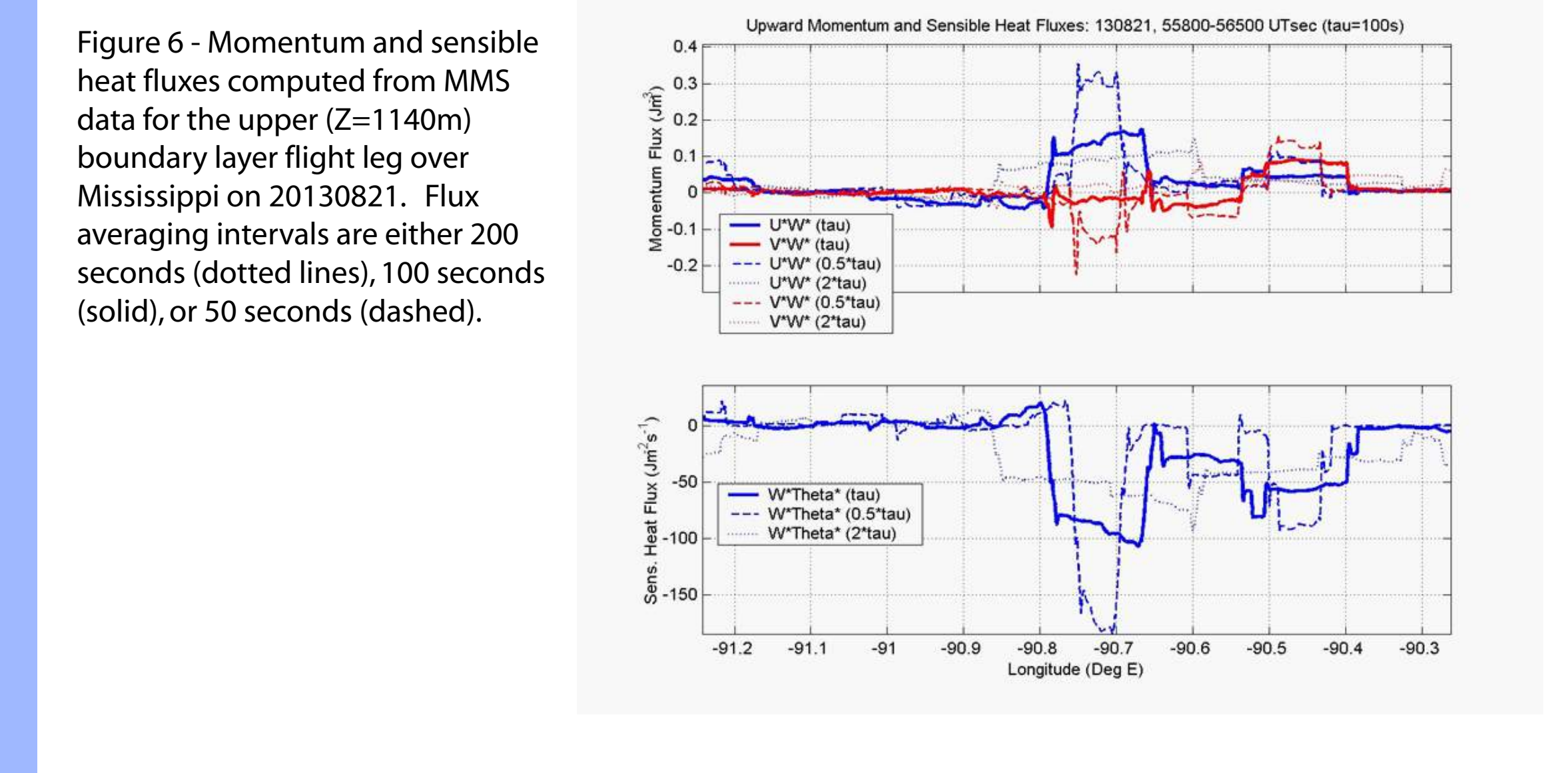
Figure 6 - Momentum and sensible heat fluxes computed from MMS data for the upper (Z=1140m) boundary layer flight leg over Mississippi on 20130821. Flux averaging intervals are either 200 seconds (dotted lines), 100 seconds (solid), or 50 seconds (dashed).

20130906 Flight above Missouri Oak Forests

On this day, the DC-8 flew a series of vertically stacked legs within the turbulent boundary layer above dense Oak forests of southeastern Missouri. The four transects flown stepped from lower to high altitude (Z = 720, 820, 1190, and 1500m). Direction of travel along the first transect was from E-W; between levels the aircraft reversed its direction so that all four segments overflew the same geographical region. Isoprene concentrations were enhanced along all four legs comprising the "flux wall" sampling. Figure 7 shows some of the MMS and in-situ chemical measurements collected on the DC-8. Vertical profiles of MMS wind and potential temperature are shown in Figure 8. An inversion layer at ~1325m divides the turbulent mixed layer below from relatively calm, free-troposphere air above, though some turbulent mixing reaches ~1500m in altitude. The boundary layer has a nearly-neutral static stability profile consistent with convective overturning from daytime heating.
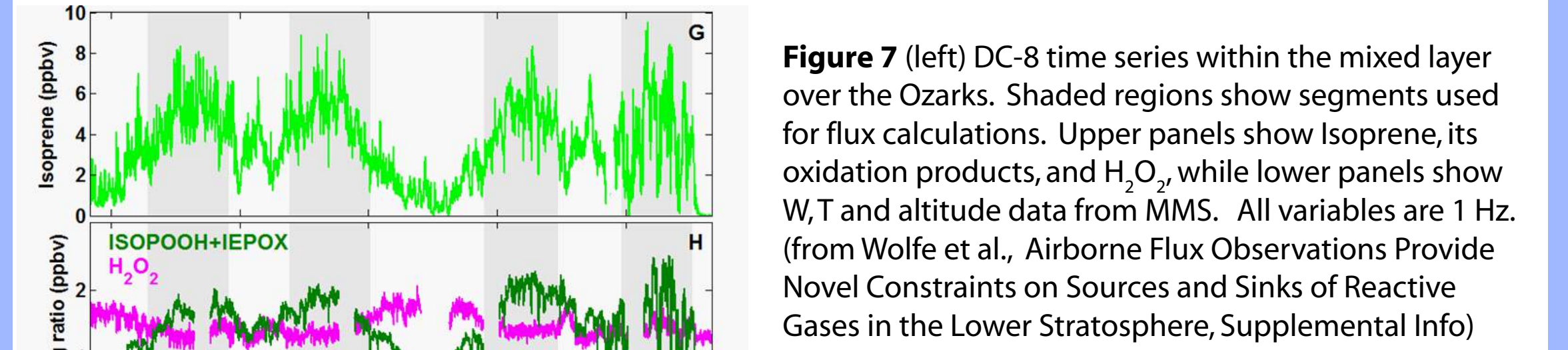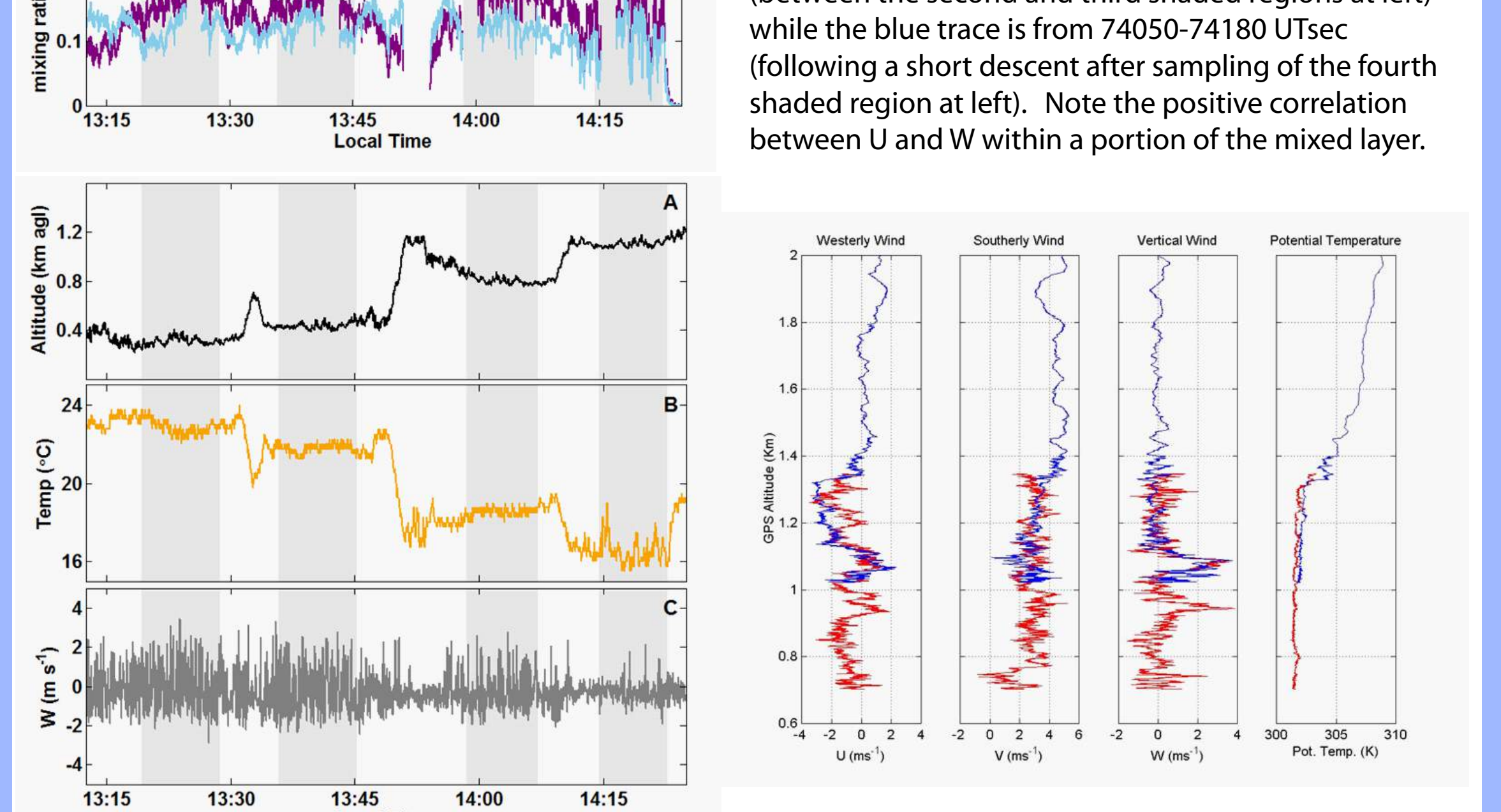
Figure 7 (left) DC-8 time series within the mixed layer over the Ozarks. Shaded regions show segments used for flux calculations. Upper panels show Isoprene, its oxidation products, and H_2O_x, while lower panels show W, T, and altitude data from MMS. All variables are 1 Hz. (from Wolfe et al., Airborne Flux Observations Provide Novel Constraints on Sources and Sinks of Reactive Gases in the Lower Stratosphere, Supplemental Info)

Figure 8 (below) DC-8 MMS 20 Hz U, V, W, and Theta profiles within and just above the mixed layer region. The red trace shows data from 71340-71480 UTsec (between the second and third shaded regions at left) while the blue trace is from 74050-74180 UTsec (following a short descent after sampling of the fourth shaded region at left). Note the positive correlation between U and W within a portion of the mixed layer.

Covariances and Dynamic Fluxes at Each Level

At Z= 720m, the MMS W spectrum follows a -5/3 turbulence cascade at frequencies >0.1 Hz, while the W-Theta cospectrum shows a strong positive correlation indicative of upward sensible heat flux. A spectral gap in the Theta spectrum below 0.04 Hz agrees with the W-Theta Ogive plot which shows a marked slope change at this frequency. This prescribes an averaging period of 25 seconds for the heat flux. Analysis of U-W and V-W cospectra indicates a similarly short averaging interval of 60 seconds for momentum fluxes. Therefore, dynamics prevent vertical transport of at sampling time scales > one minute at this level.
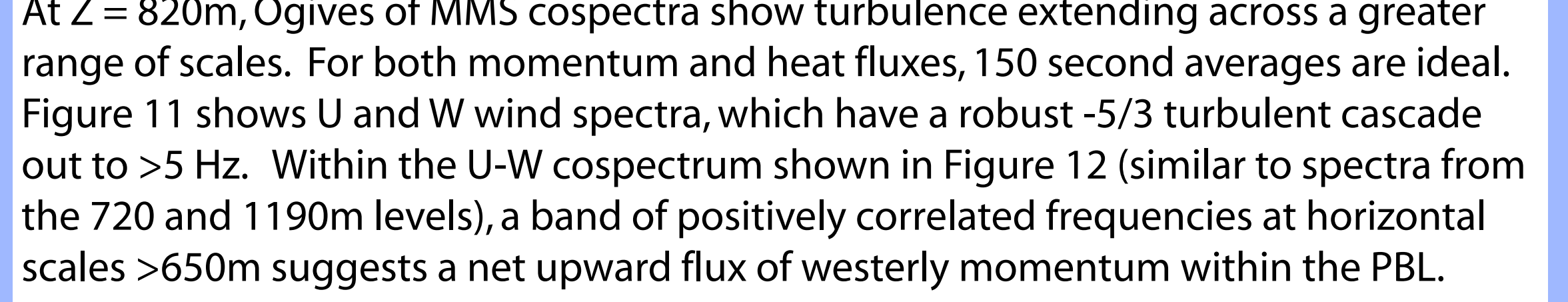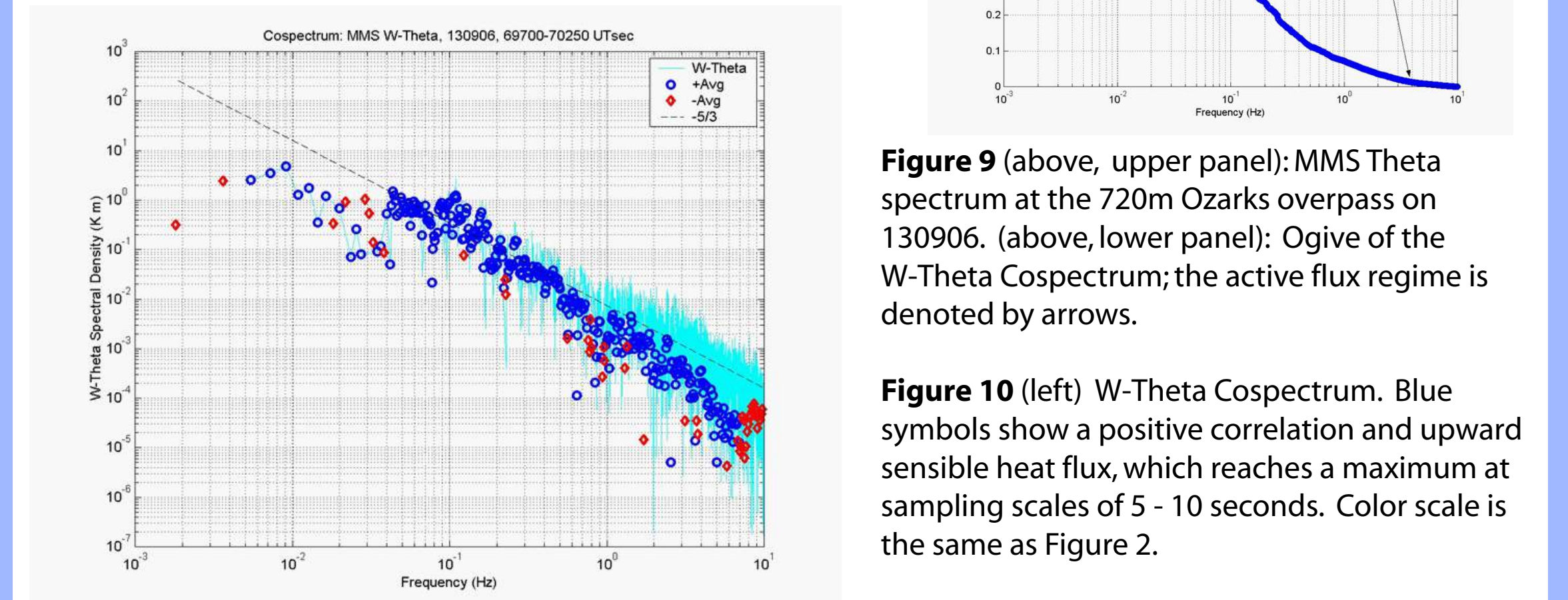
Figure 9 (above, upper panel): MMS Theta spectrum at the 720m Ozarks overpass on 130906. (above, lower panel): Ogive of the W-Theta Cospectrum; the active flux regime is denoted by arrows.

Figure 10 (left): W-Theta Cospectrum. Blue symbols show a positive correlation and upward sensible heat flux, which reaches a maximum at sampling scales of 5 - 10 seconds. Color scale is the same as Figure 2.

At Z = 820m, Ogives of MMS cospectra show turbulence extending across a greater range of scales. For both momentum and heat fluxes, 150 second averages are ideal. Figure 11 shows U and W wind spectra, which have a robust -5/3 turbulent cascade out to >5 Hz. Within the U-W cospectrum shown in Figure 12 (similar to spectra from the 720 and 1190m levels), a band of positively correlated frequencies at horizontal scales >650m suggests a net upward flux of westerly momentum within the PBL.
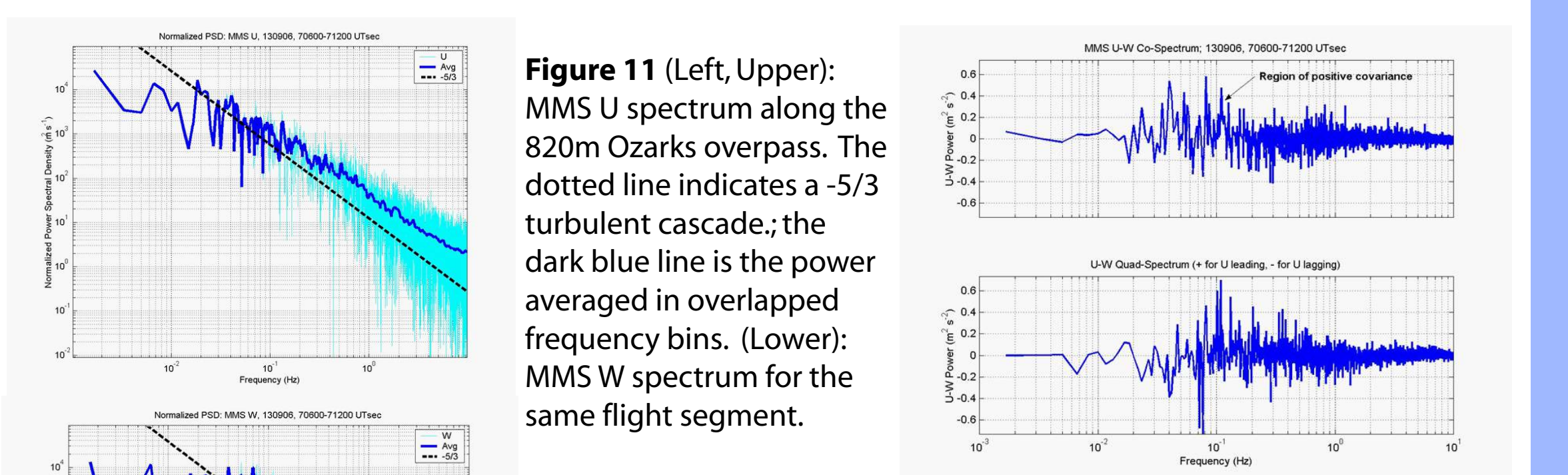
Fluxes at 820m and 1500m altitude are compared in Figure 13. The right panels show both sensible heat and momentum fluxes. Widely varying momentum fluxes at 820m contrast with much smaller values at the 1500m level. Air at the lower level

Figure 11 (Left, Upper): MMS U spectrum along the 820m Ozarks overpass. The dotted blue line indicates a -5/3 turbulent cascade; the dark blue line is the power averaged in overlapped frequency bins. (Lower): MMS W spectrum for the same flight segment.
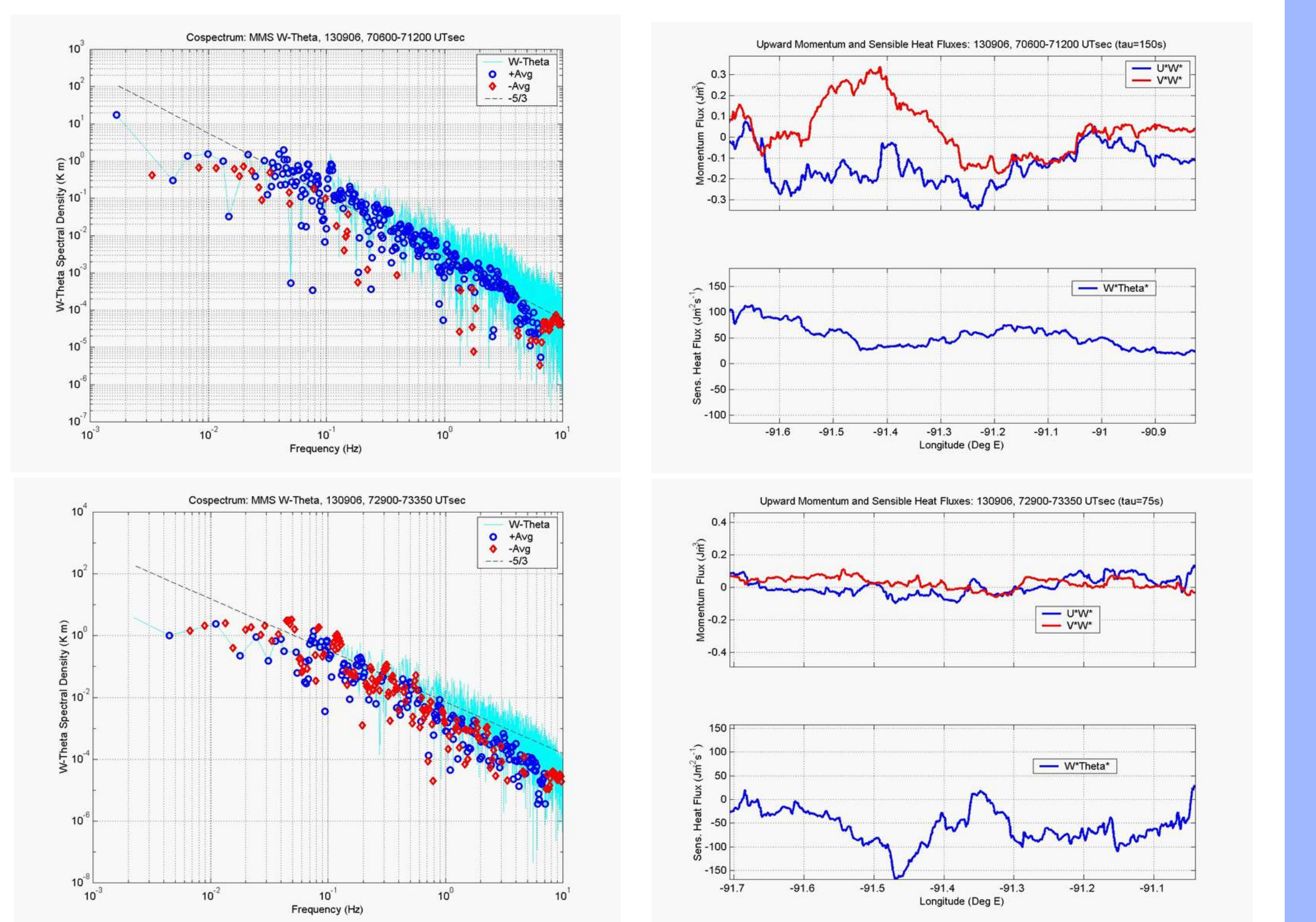
Figure 12 (Right, above): Co- and Quadrature Spectra of DC-8 MMS U and W from the 820m Ozarks overpass. In the cospectrum, a broad region of positive correlations is observed at most frequencies below 0.2 Hz.

Figure 13 (Left): W-Theta Cospectrum for the (upper) 820m, and (lower) 1500m Ozarks flight overpass. Dashed lines indicate -5/3 turbulent cascade. (Right): Momentum and sensible heat fluxes computed from MMS 20 Hz data for these flight segments. The 1500m level was above the inversion at PBL top.

Height(m)	Flux Averaging Interval (sec)		Maximum Flux Amplitude (Jm^{-3} for Momentum or $Jm^{-2}s^{-1}$ for Heat)		% of 20 Hz Dynamic Flux Captured in 1 Hz data	
	τ	H	τ_{xz}	τ_{yz}	H	τ	H
720	60	25	-0.4	0.45	300	82	84
820	150	150	-0.3	0.35	110	84	83
1190	100	100	-0.25	0.35	-50	87	85
1500	75	75	0.10	0.10	-160	82	85

Table 1 - Momentum and sensible heat fluxes computed from 20 Hz DC-8 MMS data for the Ozarks overpass on 20130906. Fluxes are maxima or minima along each flight leg; mean values are smaller. The shaded column shows areas of upward (red) and downward (blue) heat fluxes. Percentage of dynamic flux captured represents the ratio of the flux that would be evident in 1 Hz MMS data, if it were used for flux calculations, to the total flux captured in the 20Hz MMS data. See text below for discussion.

is more turbulent, while the 1500m level lies above the thermal inversion and is poorly mixed (Figure 8). Both the W-Theta cospectrum and sensible heat flux are positive at 820m, but both reverse sign at the 1190m level, and become strongly negative in the relatively stable air overlying the top of the mixed layer.

Discussion and Conclusions

Table 1 summarizes the results for the Ozarks flight. The outer scale for turbulent fluxes (i.e., averaging interval) changes at each altitude due to ambient conditions.

* Since flux magnitudes greatly depend on defining the outer scale (e.g., Figure 6), any flux calculations are valid only after (a) sufficiently sampling the air mass (sample length = 10x largest flux scale), and (b) examining the cospectral Ogives for heat and momentum fluxes to define turbulent scales of motion that impact both dynamics and chemical transport (in this case, CH_2O, C_5H_8, and their oxidation products).

* Momentum fluxes were larger and more homogeneous at the lower three altitudes where the DC-8 transected the mixed layer. These were notably less during the 1500m transect which overlayed the PBL top. Sensible heat fluxes reduced sharply with height, consistent with surface heating and a rapidly warming mixed layer.

* The proportion of these fluxes that would represented by 1 Hz sampling is insufficient to capture ~15% of the total flux. This implies that 10 Hz sampling is needed to properly resolve fluxes of either dynamic variables or chemical species in the PBL.

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