Analysis of Vertical Motion in an Urban Basin Boundary Layer

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ABSTRACT

Integration and synthesis of observations collected from diverse sources during field programs is a difficult task. We propose a four-year project to improve methods to assimilate observations collected as part of the Vertical Transport and Mixing Experiment (VTMX) field programs in order to diagnose the three-dimensional wind and thermodynamic fields within the urban basin boundary layer. The diagnostic estimates of vertical motion will provide a means to test hypotheses on vertical mixing during stable conditions and validate numerical simulations of vertical transport and mixing. We intend specifically to quantify the relative contribution, within an urban basin, of horizontal vs. vertical mass transport.

1. Background and Significance

Our proposed study focusses upon the following statement in the solicitation for proposals: “Novel approaches for obtaining and interpreting remote sensing data, combining results from a variety of instrument platforms, and relating these data to quantities that can be calculated using numerical models are also areas of research that are encouraged.” In particular, we propose to focus on the data integration aspects with direct linkages to both model evaluation and data assimiation. While data assimilation has improved significantly in recent years for spatial scales greater than 10 km, combining data collected at high temporal and spatial resolution is difficult and requires additional research and development. For example, during VTMX Intensive Observing Periods (IOPs), observations were often spaced on the order 100-1000 m in the horizontal and 10 m in the vertical.

The success of data assimilation is often judged by the degree to which it improves model simulations. However, since the underlying topography used in numerical models is heavily smoothed to damp numerical instabilities, the initial state is quickly modified as the model flow and thermodynamic fields adjust to the model’s terrain. In part, this rapid adjustment limits the potential impact of the observations in complex terrain upon the skill of simulations. As will be discussed in this proposal, integration of all available observations into a ’consistent’ depiction of the atmospheric state serves other purposes in addition to providing the best possible initial state for model simulations.

The continuum of data assimilation methods extends from successive corrections to 4-dimensional variational approaches (Thiebaux and Pedder 1987; Daley 1991). Each approach has limitations, especially when applied in urban basins during periods of stable stratification. For example, successive correction techniques (Bergthorsson and Doos 1955; Cressman 1959; Barnes 1964), which use predefined weights as a function of distance between the locations of observations and the analysis grid points, apply corrections determined from an observation on one side of a narrow mountain range that may not be representative of the conditions on the opposite side of the range. Statistical interpolation methods (Eliassen 1954), which specify observational errors according to prescribed spatial patterns, do not consider how observational errors may depend upon the local terrain and other underlying surface characteristics. Three-dimensional variational methods (Parrish and Derber 1992; Courtier et al. 1998; Rabier et al. 1998; Andersson et al. 1998) often impose dynamical constraints (e.g., thermal wind balance) that are not appropriate for local mountain-valley circulations. State-of-the-art adjoint techniques (Harms et al. 1992) focus upon minimizing future model forecast error (assuming a perfect model) rather than defining the actual (observed) state of the atmosphere. For example, if the model physical parameterizations of vertical mixing and transport are incomplete and lead to model error growth, then the initial state will be adjusted to compensate for those deficiencies, often in a manner inconsistent with the observations.

At the University of Utah, the Advanced Regional Prediction System (Xue et al. 2000, 2001a,b) Data Assimilation System (ADAS) is used to generate analyses of meteorological variables over the western United States for a variety of applications (Lazarus et al. 2002). For example, ADAS analyses of surface fields (temperature, wind, relative humidity, and pressure) typically incorporate over 2,000 surface weather observations each hour from Mesowest (Horel et al. 2002). ADAS 2-dimensional and three-dimensional analyses have been run routinely for several years and considerable subjective experience has been gleaned with respect to the successes and deficiencies of the analyses.

During the 2000 VTMX field project, 3-dimensional analyses at 1 km horizontal resolution were generated hourly for quick-look applications (Lazarus et al. 2002). We received favorable comments from many project scientists that these analyses were useful, both during and after the field project, for interpreting the temporal evolution of the stable boundary layer during the IOPs. Figure 1 provides an example of the surface wind field deduced from a 3-dimensional analysis during IOP-2 (1200 UTC 7 October, 2000) using surface observations, radiosondes, and teth-

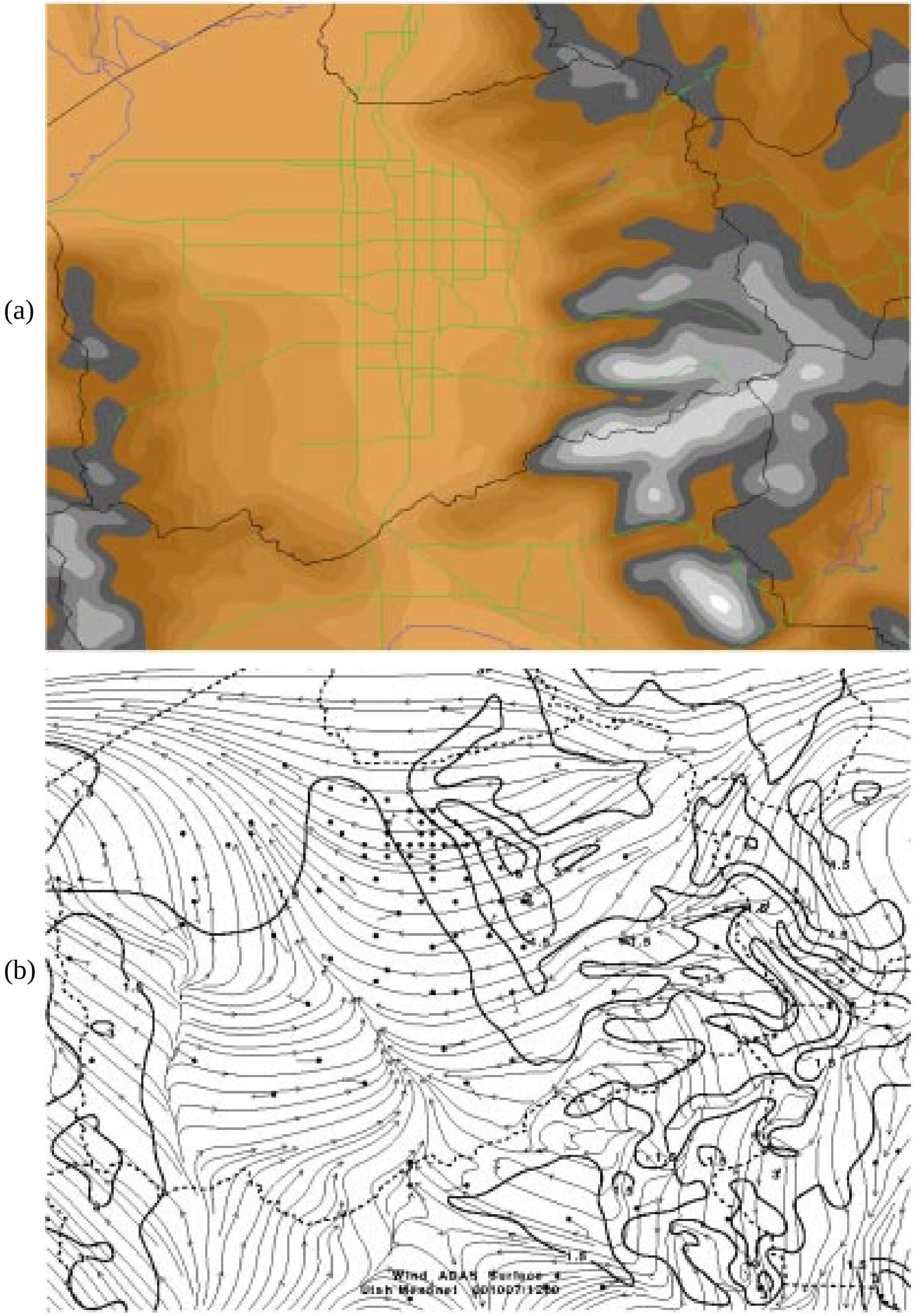

Figure 1 (a) ADAS 1 km terrain (highest terrain, light colors; county lines, dashed;), (b) 1200 UTC 7 October ADAS analysis. Streamlines (lines with arrows), surface observations (full barb, 5 m s^{-1}), interpolated wind speeds (contours, m s^{-1}), and county lines (dashed lines).

ersondes (Holland 2002). The tethersonde data ingest required some minor modifications to the analysis system and reflects the adaptability of ADAS to non-conventional data. For the case shown in Fig. 1, strong winds are evident in the northeast corner of the valley associated with a weak downslope event while the wind field in the rest of the valley is dominated by mountain/valley circulations. This downslope wind event was also sampled by a lidar (Banta et al. 2002) whose radial wind field can also be assimilated into ADAS (see Section 3b).

Following the VTMX 2000 field program, it became apparent that the analysis approach we were using had significant limitations when applied to the stable boundary layer in complex terrain. For example, we were not able to quantify the magnitude of the vertical mass transport within the stable boundary layer relative to the horizontal mass transport to/from adjacent slopes and canyons to the east and west (in the Salt Lake Valley), nor were we able to quantify the horizontal mass exchange through the Jordan Narrows to the south or over the Great Salt Lake to the north. To a certain extent, we have been hampered by incomplete observations in critical areas of the valley (for example, no continuous observations of wind were available at the northern extent of the valley or along the east bench). However, our greatest concern was that the current analysis methodology has not been able to diagnose, using available observations, the basin-wide vertical motion with sufficient accuracy. The analyses were found to have considerable sensitivity to the vertical and horizontal radii of influence, i.e., the range within which an observation influences the analysis at a particular grid point. Figure 2 (Holland 2002) provides an example of the sharp vertical variations in static stability and wind in the stable boundary layer during IOP 2 (7 October 2000); our choice of a relatively large vertical radii of influence tended to wash out these complex vertical variations in stability and wind.

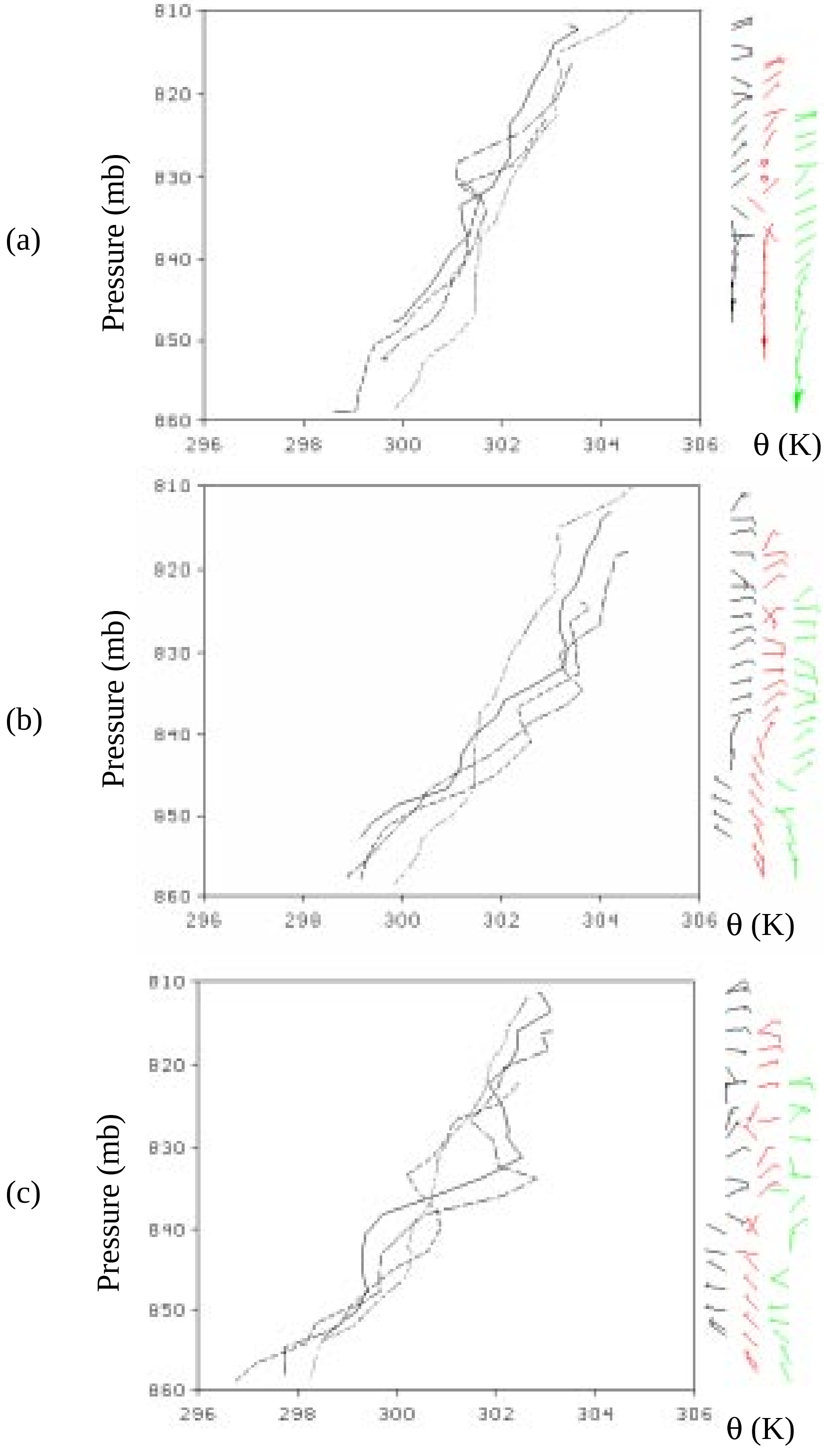

Figure 2. Potential temperature (K) vs. pressure (mb) and vector wind (m s^{-1}; full barb equals 5 m s^{-1}) from the Mt. Olivet tethersondes (solid, dash dot, dash) and Wheeler Farm radiosonde (dotted line) on 7 October at: (a) 0400 UTC, (b) 0530 UTC, and (c) 0900 UTC.

Some of the deficiencies identified in the ADAS analyses during the 2002 VTMX field program have been resolved. For example, a consistent bias during most IOPs was that exceptionally strong radiative cooling in the Rush Valley, located immediately to the southwest of the Salt Lake Valley, contributed to temperature analyses in the Salt Lake Valley that were colder than observed, especially along the west slope of the Salt Lake Valley. In order to mitigate this particular problem, we introduced an anisotropic term (e.g., Benjamin and Seaman 1985; Lanzinger and Steinacker 1990; Otte et al. 2001) to ADAS to reduce across-mountain barrier influence of corrections to the background field that are derived from surface observations in adjacent valleys (Myrick 2003). As shown in Fig. 3, the inclusion of the anisotropic term helps to alleviate this problem. For example, the analysis is cooler over the Rush and Tooele Valleys because the anisotropic term reduces the impact of the positive (warm) observation corrections from the Salt Lake Valley on the temperature analysis in the nearby valleys. Conversely, in the Salt Lake Valley, the anisotropic analysis is warmer on the west slope and east bench because the effects of negative (cool) observational corrections from the Rush and Tooele Valleys are reduced. Also significant is the warming that occurs on the leeward side of the Wasatch Mountains in data void regions. This warming is due to the restrictive nature of the anisotropic term, i.e., observation corrections from the western side of the mountains can no longer affect the analysis on the eastern side. As a result, the analysis is closer to the background field (the analysis also trends toward the background field in the data void Skull Valley).

In an attempt to further improve the analysis, we made an additional modification to ADAS by introducing a lake/sea mask that minimizes spreading corrections across coastal boundaries. This modification to ADAS is clearly evident in Fig. 3 over the Great Salt Lake, as observations over the lake at this time are warmer than those in nearby valleys.

Figure 3. Difference in temperature (°C, shaded according to scale) between anisotropic and non-anisotropic ADAS analyses for 1300 UTC 10 April 2003. Darker (lighter) shading indicates areas that were warmed (cooled) by the introduction of the anisotropic term.

Our proposed research will continue to build upon the prior research funded as part of the VTMX program (Project ID DEFGO399ER62841). Our efforts have included:

- analyzing slope flows in a remote mountain basin (Clements 2001; Clements et al. 2003)
- providing VTMX researchers with access to existing observations in the vicinity of the Salt Lake Valley (Doran et al. 2002)
- assisting with local coordination for the first VTMX field campaign during October 2000
- documenting synoptic and mesoscale characteristics of conditions during the field campaign
- examining in detail the evolution of IOP2, 7 October 2000, during which a weak downslope wind event occurred (Holland 2002)
- the integration of non-standard data streams (e.g., tethersondes) into an analysis system
- improving data assimilation methods for use in complex terrain (Lazarus et al. 2002; Myrick 2003).

2. Objectives

The primary objective of the proposed study is to test and then implement an appropriate variational constraint into ADAS that ‘balances’ the mass, temperature, and 3-dimensional wind fields. While balanced fields are a critical component of data assimilation at all scales of motion, it is not clear what constraints are both appropriate and practical at the meso-gamma scale. Ultimately, it is our goal to obtain the vertical motion field in an urban basin from the distribution of the underlying topography and observations of pressure, horizontal vector (or radial) wind, and stability. These mass balanced vertical motion fields will be determined diagnostically for the IOPs from <u>all</u> available observations on a high spatial resolution grid at frequent time intervals. Using these grids, we intend to estimate the mass budget for the entire urban basin, partitioning the estimates into a within-basin contribution due to both vertical and horizontal mass transport to/from adjacent slopes and canyons to the east and west, and the contributions due to horizontal mass exchange through the Jordan Narrows/Traverse Ridge complex to the south and the Great

Salt Lake to the north. We believe that these vertical motion fields will be of great interest to many VTMX researchers.

In addition to the aforementioned proposed work, we anticipate the following efforts in support of this project:

- investigate (and develop analysis methods which account for) the sensitivity of the predefined horizontal and vertical weights employed in ADAS to ambient conditions, i.e., stability and wind speed and direction.
- improve software required to assimilate the specialized observations available from the 2000 and 2004 VTMX Field Experiments into ADAS.
- test the variational method(s) on data collected during IOPs of the October 2000 field program in order to compare the diagnosed vertical motion fields obtained during differing states of the stable boundary layer.
- generalize the ADAS analysis system so that analysis grids can be used to initialize and validate model simulations to be run by other modeling groups.
- support the VTMX program by accessing, archiving, and disseminating weather observations collected from locations throughout the West.
- deploy 7 portable surface weather stations in support of the 2004 VTMX field program in coordination with another proposed study that includes participation from the University of Utah.

The work proposed herein encompasses all three principal categories as delineated in the solicitation (Analysis of Existing Data Sets; Field Experiments; and Improvement of VTMX Models and Modeling Approaches) and will serve to address, through data assimilation and analysis, the following science issues that are central to the VTMX program:

- Identify and quantify the fundamental processes that control vertical transport for stable and transition boundary layers.

- Improve numerical simulations and forecasts of vertical transport and mixing during stable and transition periods.
- Quantify the sensitivity of current local dispersion model predictions to variations in the treatment of vertical diffusivity and turbulence.
- Determine the nature of (and where possible, quantify) the interaction of synoptic or terrain-induced flows with cold air pools in basins, and assess how such flows affect the formation and erosion of those pools and the dispersion of pollutants in them.

The details regarding how the proposed research meets these core science issues of the VTMX program and the steps required to meet the objectives defined above follow in the next section. We view our contribution to the VTMX program as a modest project that has considerable potential to facilitate other observational and numerical studies as well as provide a means to conduct fundamental research that will benefit the understanding of urban stable boundary layers. We anticipate that the diagnostic estimates of the 3-dimensional wind field will be used by many different science teams, for example, as a means to examine the consistency between different types of observations or validate numerical simulations.

3. Research Design and Methods

a. Development of a mass conservation variational constraint

High resolution meteorological analyses can provide both three dimensional wind fields and thermodynamic information from a limited set of observations. These analyses can then be used to diagnose the transport and dispersion of pollutants in an urban basin using, for example, Lagrangian trajectory models. However, the incomplete distribution of observations in the horizontal and vertical, the lack of dynamically relevant constraints at the small scale, and the frequent rejection of observations by analysis/forecast systems are some of the principal sources of error for defining a three-dimensional wind field that is consistent with the mass and temperature fields. Most wind diagnostic techniques incorporate a form of mass conservation to ensure that their wind analysis is non-divergent (e.g., Sherman 1978; Ludwig 1991). Many of these mass-balance techniques include atmospheric stability information, which is important in complex terrain in order to properly diagnose whether the wind field is directed around or over the topography.

Wind analyses over complex (and steep) terrain are difficult to obtain, in part because it is difficult to apply lower boundary conditions and, if a mass conservation constraint is applied in three-dimensions, computationally expensive on scales of interest to the VTMX community. In light of these aforementioned issues, we propose to implement first a modification to the two-dimensional wind diagnostic technique currently used by ADAS. The immediate goal is to develop an improved estimate of the vertical motion field that takes into account the thermodynamics/stability information made available by the ADAS temperature and moisture analyses. We anticipate that the proposed work with the 2-dimensional adjustment will then lead to the development of a more complete 3-dimensional mass conserving variational constraint.

The version of ADAS at the University of Utah uses the National Center for Environmental Prediction Rapid Update Cycle Version 2 (RUC2) 20-km resolution analysis for the initial background (first-guess) field. The background field is blended with observations using the Bratseth method of successive corrections (Bratseth 1986). ADAS produces three-dimensional analyses of pressure, temperature, relative humidity and the *horizontal* wind components on a terrain-following grid. Using the ADAS analysis winds (which are a ‘blended’ combination of the first-guess RUC and all available surface and upper air observations), the vertical velocity is *diagnosed* via the O’Brien (1970) technique. The ADAS wind field is then ‘adjusted’ by minimizing the following functional J:

$$J(u, v, \lambda) = \int_{\Omega} \left\{ (u^a - u)^2 + (v^a - v)^2 + \lambda\left(\frac{\partial u^a}{\partial \xi} + \frac{\partial v^a}{\partial \eta} + \frac{\partial W_c}{\partial \zeta} \right) \right\} d\Omega, \tag{1}$$

where ξ, η, and ζ are the ADAS curvilinear coordinates, λ is the Lagrange multiplier, u and v are the input horizontal wind components from the ADAS analysis, W_c is the contravariant vertical velocity obtained from the O’Brien technique (O’Brien 1970), Ω is a two-dimensional coordinate surface (ξ, η), and the superscript ‘a’ denotes the adjusted wind components. Minimization of (1) with respect to u^a and v^a yields two Euler-Lagrange equations,

$$\begin{aligned} u^a &= u + \frac{\partial\lambda}{\partial\xi} \\ v^a &= v + \frac{\partial\lambda}{\partial\eta}. \end{aligned} \tag{2}$$

Differentiating u_a with respect to ξ, and v_a with respect to η, we obtain a two-dimensional Poisson equation in terms of λ that can be solved iteratively. Once λ is known, the *adjusted* wind components are determined directly from (2).

Estimates of vertical velocity using the O’Brien technique are prone to error over complex terrain due in part to the spurious horizontal divergence associated with observational errors as well as errors related to the representativeness of observations in steep orography. These errors are not removed by (1), since only the horizontal components are ‘adjusted’. Hence, the adjustment process, which ensures that the horizontal components analyzed by ADAS are minimally adjusted (in a least squares sense) and satisfy mass conservation, forces the horizontal wind components to carry the burden of balancing the three-dimensional wind field. The amount of ‘balancing’ required will likely be minimal as the adjustments to the horizontal flow forced by Eq. (1) are driven by the residual three-dimensional column-integrated divergence, which the O’Brien method minimizes.

As a first step, we propose to improve the O’Brien method so that it incorporates information regarding the ambient static stability. In this manner, vertical motion estimates are therefore coupled both dynamically (through mass conservation) and thermodynamically (through static stability), thereby producing a more consistent three-dimensional wind field analysis in complex terrain.

The O’Brien method can be defined as a minimization of the following functional

$$J = \int_{\zeta} \left[\frac{\partial u^*}{\partial\xi} + \frac{\partial v^*}{\partial\eta} + \alpha_v \frac{\partial W_c^{*a}}{\partial\zeta} \right]^2 d\zeta, \tag{3}$$

where $u^* = \rho u$, $v^* = \rho v$ are the 'analysis' wind components and $W_c^{*a} = \rho W_c^a$ is the adjusted contravariant vertical velocity (multiplied by the air density). For the traditional O'Brien method, the weight $\alpha_v = 1.0$. However, here we will specify α_v to be a function of the ambient stability. Note that α_v can be constant across the domain or can vary both spatially and temporally. It can be shown that the 'modified' O'Brien estimate of vertical velocity is

$$W_c^{*a}(\zeta) = \frac{1}{\alpha_v}\left\{\frac{\zeta}{H}\int_0^H\left(\frac{\partial u^*}{\partial \xi} + \frac{\partial v^*}{\partial \eta}\right)d\zeta' - \int_0^\zeta\left(\frac{\partial u^*}{\partial \xi} + \frac{\partial v^*}{\partial \eta}\right)d\zeta'\right\} \tag{4}$$

As mentioned previously, for $\alpha_v = 1.0$, Eq. (4) is the traditional O'Brien method. If we take the difference between the mass conservation equation for an incompressible fluid and subtract that from our 'modified' mass conservation equation as defined in Eq. (3) we have

$$\frac{\partial W_c^{*a}}{\partial \zeta}[\alpha_v - 1] = \delta \tag{5}$$

where δ is the 'extra' divergence, i.e. deviation from actual mass conservation. Hence, the vertical motion obtained from the modified O'Brien method is *consistent* with respect to mass conservation only if $\delta = 0$. By 'consistent' we mean that the vertical velocity obtained via Eq. (3) (with $\delta = 0$) does **not** exactly conserve mass because it is applied as a weak constraint. Note however that we then proceed to adjust the horizontal (ADAS analyzed) components via Eqs. (1) and (2) - thereby ensuring that final wind field (post-adjustment) conserves mass.

Although the traditional O'Brien technique does not conserve mass exactly, its vertical motion field minimizes the column divergence. The introduction of the weight, α_v, essentially mitigates the minimization process - producing excess three-dimensional divergence (over that of the traditional method). This excess divergence is then removed via adjustment of the horizontal velocities using Eqs. (1) and (2).

The basic idea behind the addition of a static stability parameter is to shift the burden of mass balance from the vertical to the horizontal flow when the atmosphere is stably stratified ($\alpha_v >> 1$).

We propose here to take advantage of the thermodynamic information provided by ADAS to determine the degree to which the horizontal flow is redirected around the topography. Following Sugiyama and Chan (1997), where

$$\begin{aligned} \frac{1}{\alpha_v} &= e^{-1.5(Str)^{1.5}}, \; Str \geq 0 \\ \frac{1}{\alpha_v} &= e^{1.5(-Str)^{1.5}}, \; Str < 0 \end{aligned} \tag{6}$$

A <u>local</u> Strouhal (Str) number can be defined as

$$\begin{aligned} Str &= \frac{HN}{U}, \; N = \sqrt{\frac{g}{\theta}\frac{d\theta}{dz}}, \; \frac{d\theta}{dz} \geq 0, \\ Str &= -\frac{H}{Ut}, \; \frac{1}{t} = \sqrt{-\frac{g}{\theta}\frac{d\theta}{dz}}, \; \frac{d\theta}{dz} < 0 \end{aligned} \tag{7}$$

The characteristic height, H, (which takes into account the terrain variation), and charactertistic velocity field, U (magnitude of the horizontal flow) can be defined locally. For a neutral lapse rate (Strouhal = 0), $\alpha_v = 1.0$ and the solution for the vertical motion is that for the traditional O’Brien technique. In the limit of increasing stability $1/\alpha_v$ approaches zero and thus W_c is not adjusted (i.e. remains near zero everywhere in the column). As the stability increases, $\partial W_c^* / \partial \zeta \sim 0$ everywhere, and thus mass balance is achieved [using Eq. (1)] by squeezing the divergence out of the horizontal flow, which in turn should lead to larger adjustments in the analyzed horizontal components of the wind.

Despite the global nature of the adjustments (i.e., adjustments in the wind field are domain wide) associated with the minimization of Eq. (1), preliminary tests of the coupled two-dimensional mass balance/modified O’Brien technique suggest that the approach is promising. However, we anticipate the need for additional modifications in order to ensure that the analysis remains constrained by *local* observations. These adjustments may include performing the O’Brien technique between each of the multiple successive correction passes through the data and/or performing the 2-dimensional adjustment as defined by Eqs. (1) and (2) locally, i.e., over subregions of the analysis domain at scales of motion relevant to VTMX.

A fully three-dimensional variational adjustment of the wind field to conserve mass as a function of stability is likely to be the best approach, and will be pursued during the latter years of this project. Lazarus et al. (2000) presented preliminary work on one approach to accomplish this objective. While this approach shows promise, it requires considerable computational time to solve for the balanced wind field at high spatial resolution.

b. Additional Improvements to ADAS

Lazarus et al. (2002) and Myrick (2003) have demonstrated ways in which ADAS can be improved in order to diagnose the three-dimensional wind in stable boundary layers. Additional modifications to ADAS that we intend to explore include adjusting the weights applied to the differences between observations and the background field as a function of the atmospheric state, e.g., increasing (decreasing) the horizontal (vertical) distance over which observation corrections are applied as the wind speed (stability) increases. Benjamin and Seaman (1985) have shown the benefits, for synoptic scales of motion, of defining the analysis weights as a function of both wind speed and direction. Similar procedures might help to diagnose the vertical mixing and transport associated with such phenomena as the penetration of the lake breeze into the Salt Lake Valley during the afternoon transition period and nocturnal penetration of gap flows into the basin.

Based on the preliminary 3-dimensional analyses that we completed for the IOPs during the October 2000 VTMX field campaign, additional software is required to improve the assimilation of the many specialized observations available from the 2000 and 2004 VTMX field experiments. These changes range from simple ones, i.e., removing the assumption that rawinsonde balloons travel vertically, to the more complicated, i.e., the direct insertion of lidar radial wind observations into the analysis. The latter requires modification of existing code for insertion of WSR-88D radial wind observations. We also intend to improve our quality control algorithms to identify and discard observations that are not consistent thermodynamically and dynamically with nearby observations in space and time.

In an effort to facilitate and encourage the use of the ADAS analyses, we also propose to generalize the ADAS analysis system so that analysis grids can be used to initialize and evaluate model simulations performed by other modeling groups. We currently incorporate ADAS surface analyses directly into MM5 model forecasts at the University of Utah and plan to include fully 3-dimensional boundary layer analyses into the initial state of the WRF model (a version of WRF is now being tested at the University of Utah). Ideally, model initialization should be performed using an analysis on the model's native grid. Towards this end, we will assist other modeling groups in their efforts to use ADAS in their model framework, which should in turn help to systematically test and evaluate turbulence, surface energy budget, and radiation parameterizations in their numerical models. While we have not established formal ties with laboratory scientists who have been funded for the next four years or other research groups applying for funding, initial correspondence regarding our proposed work with colleagues has been quite positive (a copy of our pre-proposal was disseminated amongst our peers).

Testing and validation of the improved data assimilation procedures will be conducted using the data collected from the October 2000 Salt Lake City VTMX field campaign. Observations during several IOPs from surface meteorological towers, tethersondes, rawinsondes, profilers, lidar, and sodars will be assimilated. We anticipate that these reanalyses will help to define the basin-scale vertical motion field and may help to document deficiencies in the earlier data collection effort that can be avoided during the second field campaign.

c. Other Research Activities

In addition to the basic research that will lead to improved numerical techniques to diagnose consistent mass, wind, and thermal fields in stable boundary layers, we intend to participate extensively in the VTMX program in collaboration with other researchers. For example, the two students proposed to be supported as part of this research project would participate in field operations; former students Craig Clements and Lacey Holland gained valuable experience working with laboratory scientists in the field. The lead Principal Investigator will also assist with local coordination for the field campaign as needed. We expect to assimilate as many observations of temperature, wind, moisture, and pressure in quasi-real time during the IOPs as possible to assist in field operations and to provide quick-look resources for the researchers following the field program.

As the research-quality field experiment data from the second field campaign become available, we propose to analyze the 3-dimensional structure of the boundary layer at 500 m horizontal resolution with 50 vertical layers below crest level during the IOPs. The analyses will be created at 15 minute intervals to define the temporal evolution of the vertical motion field. These analyses will provide support for both observational and modeling studies by integrating conventional observation sources (surface and upper air observations, aircraft reports, etc.) with the unconventional data streams collected during the field program in addition to producing data sets from which to initialize and evaluate numerical simulations. We expect to collaborate extensively with groups collecting observations in order to provide some context for their observations relative to those collected in other parts of the basin.

We also intend to support the VTMX program by accessing, archiving, and disseminating weather observations throughout the West. This ongoing effort has been relied upon by many VTMX researchers. Significant improvements have been made since the first field program (including additional observations in the Salt Lake Valley) and data collection now spans the entire nation. This data resource provides a means to contrast the role of vertical mixing and transport in the Salt Lake Valley to other urban basins around the nation. Similar to the support provided during the first field program, seven portable surface weather stations are proposed to be deployed in coordination with the proposed study by Greg Poulos and Joseph Warne, Colorado Research Associates, and Jim Steenburgh, University of Utah. Several of those portable stations will be deployed along the Traverse Ridge at the southern end of the Salt Lake Valley in order to deduce the role of interbasin transport; others will be deployed at locations necessary to fill in gaps in the observational network and thereby improve basin-wide estimates of horizontal divergence and vertical motion.

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Myrick, D. 2003: *An Improvement to Data Assimilation over Complex Terrain.* M.S. Thesis. University of Utah.

O'Brien, James J. 1970: Alternative solutions to the classical vertical velocity problem. *J. Appl. Meteor.*, **9**, 197-203.

Otte, T. L., N. L. Seaman, and D. R. Stauffer, 2001: A heuristic study on the importance of anisotropic error distribution in data assimilation. *Mon. Wea. Rev.*, **129**, 766-783.

Parrish, D. F., and J. C. Derber, 1992: The National Meteorological Center's spectral statistical-interpolation analysis system. *Mon. Wea. Rev.*, **120**, 1747-1763.

Rabier, F., A. McNally, E. Andersson, P. Courtier, P. Unden, J. Eyre, A. Hollingsworth, and F. Bouttier, 1998: The ECMWF implementation of three-dimensional variational assimilation (3DVAR). Part II: Structure functions. *Quart. J. Roy. Meteor. Soc.*, **124**, 1809-1829.

Sasaki, Y., 1971: A theoretical interpretation of anisotropically weighted smoothing on the basis of numerical variational analysis. *Mon. Wea. Rev.*, **99**, 698-707.

Sashegyi, K. D., D. E. Harms, R. V. Madala, and S. Raman, 1993: Application of the Bratseth scheme for the analysis of GALE data using a mesoscale model. *Mon. Wea. Rev.*, **121**, 2331-2350.

Seaman, R. S., 1988: Some real data tests of the interpolation accuracy of Bratseth's successive correction method. *Tellus*, **40**(A), 173-176.

Sherman, Christine A. 1978: A mass-consistent model for wind fields over complex terrain. *J. Appl. Meteor.*: **17**, 312-319.

Steinacker, R., C. Haberli, and W. Pottschacher, 2000: A transparent method for the analysis and quality evaluation of irregularly distributed and noisy observational data. *Mon. Wea. Rev.*, **128**, 2303-2316.

Thiebaux, H. J., and M. A. Pedder, 1987: *Spatial Objective Analysis*. Academic Press, 299 pp.

Xue, M., K. K. Droegemeier, and V. Wong, 2000: The Advanced Regional Prediction System (ARPS) - A multiscale nonhydrostatic atmospheric simulation and prediction tool. Part I: Model dynamics and verification. *Meteor. Atmos. Phys.*, **75**, 161-193.

5. Programmatic Issues

a. Joint Proposal

A cover letter is attached to this proposal that repeats the following information in order to explain the programmatic benefits for this joint proposal from the University of Utah and Florida Institute of Technology rather than a subcontract from one university to the other. Drs. Horel, Lazarus, and Potter were the Principal Investigators of the project funded during the past 4 years at the University of Utah as part of the VTMX program. Dr. Potter retired last year and Dr. Lazarus accepted a faculty position at Florida Institute of Technology during 2001. Drs. Horel and Lazarus have continued to collaborate extensively on VTMX-related research with a subcontract from the University of Utah to Florida Institute of Technology. For example, Dr. Lazarus has served actively on the M.S. committee for D. Myrick, who is nearing completion for the requirements for the M.S. degree. At this point in Dr. Lazarus's career, it is important to establish funding directly from the Department of Energy as opposed to continuing the present subcontract arrangement; it will be equally beneficial for the Department of Energy to support his research directly.

b. Division of Research Effort and Timeline

Each Principal Investigator will lead clearly defined areas of research. Dr. Lazarus will lead the effort to develop variational constraints into ADAS that will help to define the three dimensional wind field. The focus during Year 1 will be to implement and test the enhancement to the O'Brien technique described in Section 3a. Research will then continue during subsequent years to develop and test variational constraints to conserve mass in three dimensions. In addition, versions of the ADAS software appropriate for use in other modeling systems will be developed in the later years.

Dr. Horel will lead the software development to incorporate additional adjustments to the ADAS weighting scheme and improve software to assimilate specialized observations during Year 1. Using computational resources available at the University of Utah, Dr. Horel will coordinate the reanalysis for the IOPs during October 2000 during Year 1. After the completion of the September 2004 field program, Dr. Horel will reanalyze the dynamical and thermodynamical fields for the field program using all available observations in order to define the mass budget for the urban basin.

c. Budget Explanation

The major costs of the proposed research are partial support for 2 graduate students (.5 FTE at each university) and 1 month of summer salary for each Principal Investigator. Travel expenses for the graduate student at Florida Institute of Technology for the period of the field experiment are also anticipated (airfare $600; 30 days per diem @ $30 per day; and lodging 30 days @ $65 per day) as well as partial support for Dr. Lazarus during that period (airfare $600; 10 days per diem @ $30 per day; rental car $30 per day for 10 days; and lodging 10 days @ $65 per day). Dr. Lazarus will also attend one preplanning meeting at Salt Lake City (airfare $600, 1 night lodging @ $70 and per diem $30). Travel expenses during the later years for Dr. Lazarus are required to attend VTMX planning meetings likely to be held in Salt Lake City and to facilitate research activities between the two university groups (2 trips to Salt Lake City per year: airfare $600 each, 4 nights lodging each @ $70 per night; plus per diem @ $30 per day for four days). Travel costs for Dr. Horel are requested every other year to visit Florida Institute of Technology to coordinate research and to attend national meetings to present research results in the alternate years (airfare $600; 4 nights lodging each @$70 per night plus per diem @ $30 per day for four days). Publication costs are expected during each year as a result of prior research that is nearing completion (Holland and Myrick thesis research, for example). Funds are requested for technical supplies (computer disks, tapes, etc.) in order to store and archive data and the analyses at each university.

7. Biographical Sketches

John D. Horel
Professor, Meteorology
University of Utah

EDUCATION

Ph.D. 1982, Atmospheric Sciences, University of Washington
B.S. 1977, Meteorology, San Jose State University

PROFESSIONAL EXPERIENCE

1996-present, Professor, Meteorology, University of Utah
2002-present, Director, NOAA Cooperative Institute for Regional Prediction, University of Utah
1996-1998, Acting Director, NOAA Cooperative Institute for Regional Prediction, University of Utah
1990-1996, Associate Professor, Meteorology, University of Utah
1986-1990, Assistant Professor, Meteorology, University of Utah
1982-1986, Assistant Research Professor, Scripps Institution of Oceanography

RESEARCH ACTIVITIES

Prof. Horel's research is centered on the observation and analysis of weather processes in complex terrain. He helped to establish the NOAA Cooperative Institute for Regional Prediction, which conducts a broad program of research that includes efforts towards improving weather and climate prediction in regions of complex terrain. Current research activities include the development of MesoWest, which provides access to surface weather observations for operational, research, and educational applications.

AWARDS

College of Mines and Earth Sciences Outstanding Teacher Award 1993-94
Fellow of the American Meteorological Society 2002

SELECTED PUBLICATIONS

Horel, J.D., and J. E. Geisler, 1996: *Global Environmental Change: An Atmospheric Perspective.* 165 pp. John Wiley and Son.

Schultz, D. M., W. J. Steenburgh, R. J. Trapp, J. Horel, D. E. Kingsmill, L. B. Dunn, W. D. Rust, L. Cheng, A. Bansemer, J. Cox, J. Daugherty, D. P. Jorgensen, J. Meitin, L. Sho well, B. F. Smull, K. Tarp, and M. Trainor, 2002: Understanding Utah winter storms: The Intermountain Precipitation Experiment. *Bull. Amer. Meteor. Soc.*, **83**, 189-210.

STEVEN LAZARUS

Florida Institute of Technology
Department of Marine and Environmental Systems
150 W University Boulevard Melbourne, FL 32901
email: slazarus@fit.edu

Work Telephone
(321) 394-2160

EDUCATIONAL BACKGROUND

Ph.D Meteorology	University of Oklahoma	Fall 1996
Dissertation: *The assimilation and prediction of a Florida multicell storm using single-Doppler data*		
M.S. Meteorology	University of Oklahoma	Fall 1990
Thesis: *The influence of helicity on the stability and morphology of numerically simulated storms*		
B.S. Meteorology (Cum Laude)	Florida State University	Fall 1985

HONORARY SOCIETIES, AWARDS, & EXTRACURRICULAR ACTIVITIES

NCAR-ECSA Junior Faculty Forum participant (June 2003)
COMET workshop on Atmospheric Thermodynamics participant (August 2002)
AMS Salt Lake City chapter president 2000-2001
Mentor for a Salt Lake City Homeless Shelter child, 1997-2001
Allan Saxe Scholarship recipient 1988
Alpha Epsilon Lambda Society
Student Development Award of Excellence
Recognition for contributions made to OU as chair of Graduate Student Senate
Member, American Geophysical Union
Member, American Meteorological Society

WORK HISTORY

Assistant Professor, Florida Institute of Technology	8/01 - present
Research Assistant Professor, University of Utah	10/99 - 7/01
Post-Doctoral Research Associate, University of Utah	1/97 - 9/99
Research Assistant (Ph.D), University of Oklahoma School of Meteorology	1/91 - 12/96
Research Assistant (M.S.), University of Oklahoma School of Meteorology	8/86 - 12/90
Research Assistant at Stennis Space Center, Bay St. Louis MS	1/86 - 8/86
Undergraduate Research Assistant, Florida State University (FSU Air-Sea Interaction Group, Dr. James J. O'Brien)	1/84 - 12/85
Undergraduate fellowship, University of Chicago (Dr. Theodore Fujita)	Summer 1984

RESEARCH ACTIVITIES/CURRENT FUNDING

Analysis of the Planetary Boundary Layer over an Urban Valley
Vertical Transport and Mixing Experiment. Co-PI, NOAA grant (2000-2004 #ER 62841-1013411-0005009).
Parameterization of Clouds and Convection in the NCEP Global Model ARM/DOE grant (2001-2003).
Operation Center Coordinator - VTMX project Salt Lake City October 2000.
Field Volunteer Coordinator - VTMX project Salt Lake City October 2000.
2002 Winter Olympic support work (near real-time analyses)
Evaluation of solar and wind energy associated with the Florida sea breeze - PI,
Florida Solar Energy Commission (2002-2003)
Assimilation of MODIS Temperature and Water Vapor Profiles into a Mesoscale Analysis: COMET
Partnership (NOAA, 2003-2004)

REFEREED PUBLICATIONS

Droegemeier, K.K., S.M. Lazarus, and R. Davies-Jones, 1993: The influence of helicity on numerically simulated convective storms. *Mon. Wea. Rev.*, **121**, 2005-2029.

Lazarus, S. M., A. Shapiro, and K. D. Droegemeier, 1999: Analysis of the Gal-Chen single-Doppler velocity retrieval. *J. Atmos. Oceanic Technol*., **16**, 5-18.

Lazarus, S. M., S.K. Krueger, and G. G. Mace, 2000: A cloud climatology of the Southern Great Plains ARM CART. *J. Climate*, **13**, 1762-1775.

Lazarus, S. M., A. Shapiro, and K. D. Droegemeier, 2001: Application of the Gal-Chen/Zhang single-Doppler velocity retrieval to a deep convective storm. *J. Atmos. Sci.*, **58**, 998-1016.

Lazarus, S. M., J. D. Horel, and C. M. Ciliberti, 2002: Application of a near-real time analysis system in complex terrain. *Wea. Forecasting*, **17**, 971-1000.

J. Horel, M. Splitt, L. Dunn, J. Pechmann, B. White, C. Ciliberti, S. Lazarus, J. Slemmer, D. Zaff, and J. Burks, 2002: Mesowest: Cooperative Mesonets in the Western United States. *Bull. Amer. Met. Soc.*, **83**, 211–226.

CONFERENCE PAPERS

Lazarus, S. M., 2002: An intercomparison of MMCR and NCEP Global Model Clouds at the ARM SGP Site. Preprints, 11th Conference On Cloud Physics, Ogden Utah, Amer. Met. Soc., June 3-7.

Lazarus, S. M., 2002: An intercomparison of MMCR and NCEP Global Model Clouds at the ARM SGP Site. Preprints, 12th Annual ARM Science Team Meeting, St. Petersburgh Florida, April 8-12.

Horel, J. D., Ciliberti, C. M., and S. M. Lazarus, 2001: Data Assimilation over the Western United States. Preprints, 5th Symposium on Integrated Observing Systems, Albuquerque New Mexico, Amer. Met. Soc., Jan. 14-19.

Ciliberti, C.M., John D. Horel, and Steven M. Lazarus, 1999: An analysis of a cold frontal passage over complex terrain in northwest Utah. Preprints, Eighth Conference on Mesoscale Processes, Boulder Colorado, Amer. Met. Soc., 459-462.

Janish, P.R., M.L. Branick, K.K. Droegemeier, M. Xue, K. Brewster, J. Levit, A. Sathye, R. Carpenter, A. Shapiro, V. Wong, Y. Liou, D. Wang, H. Jin, X. Song, D. Weber, S. M. Lazarus, G. Bassett, M. Zou, N. Lin, and L. Sun, 1994: Evaluation of the Advanced Regional Prediction System (ARPS) for storm scale operational forecasting during VORTEX ’94. Abstract, 1994 Fall Meeting of the American Geophysical Union, 5-9 December, San Francisco.

Krueger, S. K., S. M. Lazarus, G. G. Mace, and K. Sassen, 1997: Structure of a continental stratocumulus-topped boundary layer observed by aircraft and cloud radar. Preprints, 12th Symposium on Boundary Layers and Turbulence, Vancouver, B. C., Canada, Amer. Met. Soc., 66-67.

Krueger, S. K., and S. M. Lazarus, 1998: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving and single-column models. Proceedings of the Eighth Atmospheric Radiation Measurement (ARM) Science Team Meeting, Tucson, Arizona, DOE, (in press).

Krueger, S. K., and Lazarus, S. M., 1998: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving and single-column models. Proceedings, CLIVAR/GEWEX COARE98 Conference, Boulder, CO, WCRP, 351-352.

Krueger, S. K., and S. M. Lazarus, 1999: Intercomparison of multi-day simulations of convection during TOGA COARE with several cloud-resolving and single-column models. Preprints, 23rd Conference on Hurricanes and Tropical Meteorology, Dallas, TX, Amer. Meteor. Soc., 643-647.

Lazarus, S.M. and K.K. Droegemeier, 1988: Simulation of convective initialization along gust fronts. Preprints, 15th Conf. on Severe Local Storms, Amer. Meteor. Soc., Feb. 22-26, Baltimore, 107-110.

Lazarus, S.M. and K.K. Droegemeier, 1990: The influence of helicity on the stability and morphology of numerically simulated storms. Preprints, 16th Conf. on Severe Local Storms, Kananaskis Provincial Park, Alberta Canada, Amer. Meteor. Soc., 269-274.

Lazarus, S.M., J. D. Horel, and C. M. Ciliberti, 2000: Wind analysis in complex terrain. 9th Conference on Mountain Meteorology, Amer. Meteor. Soc., Aug. 7-11, Snowmass Village, CO.

Lazarus, S.M., C. M. Ciliberti, and J. D. Horel, 1998: Application of a local analysis system in highly variable terrain. 16th Conference on Weather Analysis and Forecasting, Pheonix Az., Amer. Meteor. Soc., Jan. 11-16.

Lazarus, S.M., S. K. Krueger, and G. G. Mace, 1998: A cloud climatology of the ARM SGP CART. Proceedings of the 8th Atmospheric Radiation Measurement (ARM) Science Team Meeting, Mar 23-27, Tucson, AZ, 413-416.

Lazarus, S.M., S. K. Krueger, and S. A. Frisch, 1999: An evaluation of the Xu-Randall cloud fraction parameterization using ASTEX data. Preprints, 13th Symposium on Boundary Layers and Turbulence, Dallas, TX, Amer. Met. Soc., 582-585.

Lazarus, S.M., S. K. Krueger, and S. A. Frisch, 1999: An evaluation of the Xu-Randall cloud fraction parameterization using ASTEX data. Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team meeting, San Antonio, Texas, DOE. Extended abstracts on-line.

Lazarus, S.M., M.E. Splitt, C.M. Ciliberti, and Mark Miller, 1999: Application of a cloud/mesoscale analysis system to estimate hydrometeor advection over the SGP ARM CART. Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team meeting, San Antonio, Texas, DOE. Extended abstracts on-line.

Shapiro, A. and S.M. Lazarus, 1993: A modified dynamic recovery technique for cloud-scale numerical models. Preprints, 17th Conf. on Severe Local Storms, Amer. Meteor. Soc., Oct. 4-8, St. Louis, 455-459.

Shapiro, A., K.K. Droegemeier, S. Lazarus, and S. Weygandt, 1994: Forward variational four-dimensional data assimilation and prediction experiments using a storm-scale numerical model. Proc., Int. Symp. on Assimilation of Observations in Meteor. and Oceanography, 13-17 March, World Meteorological Organization, Tokyo.

GRADUATE STUDENT THESIS COMMITTEES

Carol Ciliberti	University of Utah Ph.D student
Lacey Holland	University of Utah M.S. student
Karen Sonntag	University of Utah M.S. student
David P. Yorty	University of Utah M.S. student
Dave Myrick	University of Utah M.S. student
Brad Zavodsky	Florida Institute of Technology (advisor)

Horel, J., M. Splitt, L. Dunn, J. Pechmann, B. White, C. Ciliberti, S. Lazarus, J. Slemmer, D. Zaff, J. Burks, 2002: MesoWest: Cooperative Mesonets in the Western United States. *Bull. Amer. Meteor. Soc.*, 83, 211-226.

Horel, J., T. Potter, L. Dunn, W. J. Steenburgh, M. Eubank, M. Splitt, and D. J . Onton, 2002: Weather support for the 2002 Winter Olympic and Paralympic Games. *Bull. Amer . Meteor. Soc.*, 83, 227-240.

Doran, C., J. Fast, J. Horel, 2002: The VTMX 2000 Campaign. *Bull. Amer. Meteor. Soc.*, 83, 537-551.

Lazarus, S., C. Ciliberti, J. Horel, K. Brewster, 2002: Near-real-time Applications of a Mesoscale Analysis System to Complex Terrain. *Wea. Forecasting*, 17, 971-1000.

Clements, C. B., C. D. Whiteman, J. D. Horel, 2003: Cold air pool structure and evolution in a mountain basin. *J. Appl. Meteor.* In press.

Horel, J., D., 2003: Terrain-forced mesoscale circulations. *Handbook of Weather, Climate, and Water.* John Wiley and Sons. T. D. Potter and B. R. Coleman Eds. In press.

GRADUATE STUDENT SUPERVISION

C. Jones, 1990. M.S.
T. Barker, 1991. Ph.D.
A. Hahmann, 1992. Ph.D.
L. Dunn, 1993. Ph.D.
C.Gibson, 1993. M.S.
R. Swanson, 1995. M.S.
J. Mittelstadt, 1995, M.S.
M. Braby, 1997, M.S.
J. Stiff, 1997, M.S.
A. Haynes, 1998, M.S.
B. McDonald, 1998, Ph.D.
J. Slemmer, 1998, M.S
R. Swanson, 1998.Ph.D.
C. Clements, 2001, M.S.
L. Cheng, 2002, M.S.
L. Holland, 2002, M.S.
D. Myrick, 2003, M.S.
Current: D. Myrick, D. Zumpfe

SELECTED PROFESSIONAL ACTIVITIES

Member of the American Meteorological Society Panel on Climate Variations 1994-1997
Member of the Scientific Steering Group for the Pan American Climate Systems Program of the NOAA Office of Global Programs: 1994-1999
Member of the U.S. CLIVAR Pan American Climate Studies Panel. 1999-2000
Co-Lead Instructor UCAR/COMET COMAP Course. Summer 1997

7. Current and Pending Support

John Horel

Agency	Title	Duration	Amount
NOAA	Cooperative Institute for Regional Prediction	July 2001-July 2004	$375,000
BLM	Development of a Nationwide, Web-base Real-time Weather Observation Monitor for Operational Fire Weather Applications	July 2002-April 2004	$300,000
DOE	Analysis of the Planetary Boundary Layer in an Urban Valley	Nov. 1999- Oct. 2003	$302,000
UCAR/ COMET	Road Weather in Complex Terrain	Mar. 2001- Oct. 2003	$70,000

Steven Lazarus

DOE	Analysis of the Planetary Boundary Layer in an Urban Valley	Nov. 1999- Oct. 2003	$302,000
	DOE Parameterization of Clouds and Convection in the NCEP Global Model (co-PI)	June 2001- May 2003	$360,000
UCAR/ COMET	Assimilation of MODIS Temperature and Water Vapor Profiles into a Mesoscale Analysis	Jan. 2003-2 Jan. 2004	$6000