Combining Thermodynamic and Kinematic Profilers to Observe Derived Quantities

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Individual profiling sites can tell us much about temporal changes in the atmosphere. Unless you assume a frozen field, you don’t know much about spatial changes.

Many important quantities depend on spatial gradients of the kinematic and thermodynamic fields:

- Divergence
- Deformation
- Advection

One profile site won’t be able to tell us anything that depends on spatial variability…

...but what happens when we have a network of sites?
ARM Climate Research Facility SGP Site

ARM SGP site is more than just the central facility near Lamont, Oklahoma.

Extended and boundary sites located throughout Oklahoma, Kansas.

40-50 km from central facility are four extended sites
- Each site hosts a Halo Streamline Doppler wind lidar
- Four sites (in blue) also have AERI thermodynamic profilers
The Land Atmosphere Feedback Experiment (LAFE)

August 2017 field campaign devoted to collecting observations in heterogeneous terrain to

• Observe flux profiles
• Validate MOST and turbulence parameterizations
• Map surface fluxes
• Characterize surface feedback and the moisture budget

Novel observation strategies:

• Situated at the ARM SGP site
• T, q, and wind lidar RHI scans
• Virtual tall towers at surface flux stations
• Unmanned aircraft system
• Thermodynamic profilers
LAFE IOP Days

LAFE science goals required days without significant synoptic forcing.

These are good days to focus on for this analysis to see how the atmosphere typically behaves during morning and evening transitions.

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We want days that look like this:

Not like this!
The Low Level Jet

North American LLJ key component of nocturnal weather in Southern Great Plains
- Forms via decoupling from the surface after sunset
- Inertial oscillation makes low level winds go supergeostrophic
- Predominantly southerly
- 100+ km wide, 1000s of km long
- 800 m above surface on average
- Speeds typically 20 m s\(^{-1}\)

Since the Great Plains lie to the north of the Gulf of Mexico, the southerly LLJ is a key source of water vapor via advection
Divergence

Microscopic measure of the expansion of a fluid at a point, defined as:

\[ \nabla \cdot \vec{U} \]

We’re usually interested in the kth component, which represents the horizontal divergence:

\[ D = \frac{du}{dx} + \frac{dv}{dy} \]

Horizontal convergence (negative divergence) at the surface leads to upward motion.
Vorticity

Microscopic measure of the rotation in a fluid, measured as the curl of the velocity field:

$$\omega = \nabla \times \vec{U}$$

We’re usually interested in the kth component, which represents the horizontal rotation about a vertical axis:

$$\zeta = \frac{dv}{dx} - \frac{du}{dy}$$

Dynamic effects mean that changes in vorticity are highly correlated with vertical motion.
Divergence and Vorticity are Related

Conservation of angular momentum says that when you bring mass closer to the axis of rotation, you spin faster.

Surface convergence brings mass closer together. It can only go up. This stretches the air, makes the column thinner, causes it to rotate faster.

Opposite happens with surface divergence.
Calculating Kinematic Properties

We want spatial derivatives of a vector field.

Should we project our observations onto a Cartesian grid and find derivatives using finite differences? **NO!**

Spencer and Doswell (2001) tested this method against a line integral-based method and found that:

“it is clear that the traditional method produces markedly inferior estimates of the derivative fields”

Green’s Theorem

Green’s Theorem states:

\[ \int P \, dx + Q \, dy = \iint \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \, dA \]

We can approximate this on an irregular polygon (like one defined by a bunch of profilers deployed in the field) as:

\[ \frac{\sum P \, \Delta x + Q \, \Delta y}{A} = \left( \frac{\partial Q}{\partial x} - \frac{\partial P}{\partial y} \right) \]

Look! It looks a lot like the definitions for vorticity and divergence! All we have to do is substitute in \( u \) and \( v \)!
Implementing Green’s Theorem

\[ D = \frac{du}{dx} + \frac{dv}{dy} = \frac{\sum \bar{u} \, dy - \bar{v} \, dx}{A} \]

\[ \zeta = \frac{dv}{dx} - \frac{du}{dy} = \frac{\sum \bar{u} \, dx + \bar{v} \, dy}{A} \]

1. Define a polygon with observations at the vertices
2. Find the average values of \( u, v \) along each side
3. Calculate the term for each side
   • Move counterclockwise! It’s direction dependent!
4. Sum the values for all sides
5. Divide by the area of the polygon
Evaluating at the SGP site

Right now, we’re interested in how the atmosphere typically behaves, not how it’s acting on a specific day.

Therefore: find the average values for kinematic properties on all the LAFE IOP days

• These are a good proxy for synoptically quiescent days

Interpolate all sites to a common grid

• 1 hr X 100 m
• All plots from 10 z on the morning of an IOP day to 10 the next day

Calculate $D$, $\zeta$ individually for each day, then average.
Divergence from SGP Profilers
Vorticity from SGP Profilers
Vorticity from SGP Profilers

[Diagram showing vorticity with height and time axes]
What About Advection?

Key goal of LAFE: characterize local fluxes of heat, momentum, moisture

Problem: two components to observed changes in moisture
• Local change
• Advection

To close the moisture budget, you have to account for advective change!

$$\frac{Dq}{Dt} = \frac{\partial q}{\partial t} + \vec{V} \cdot \nabla q$$
Green’s Theorem Works Here, Too!

\[ \vec{V} \cdot \nabla q = \frac{\sum \bar{q}_i (\bar{u}_i \Delta y_i - \bar{v}_i \Delta x_i)}{A} \]

Unfortunately, no AERI in the northeast corner, so we have to use a smaller triangle.

Same basic method as before applies
- Just include the mean q along each leg.

Moisture Advection from SGP Profilers

Moisture Advection

Height [m AGL]

Moisture flux \( \frac{\partial q}{\partial t} \) [g kg\(^{-1}\) h\(^{-1}\)]

Time [hours UTC]
There’s going to be two sources of uncertainty in these observations

1. Instrument uncertainty
   • How do the random measurement errors contribute to the uncertainty in the derived quantity?

2. Truncation errors
   • How does approximating the line integral with finite line segments contribute to uncertainty?
Instrument Uncertainty: Divergence

Each ARM wind profiler observation has a 1-sigma uncertainty.

Use a Monte Carlo approach.

Perturb each wind observation by a random value selected from a normal distribution with a mean of 0 and the ARM-derived standard deviation.

This shows standard deviation of divergence calculation for $1 \times 10^5$ perturbations of each wind observation.

Uncertainty goes way down at night due to reduction in solar scattering.
Vorticity uncertainty looks almost identical to the divergence.

Differences are 2 orders smaller than the observation.

Since vorticity and divergence are very similar linear combinations, not surprising that overall uncertainties are effectively the same after so many perturbations.

Instrument uncertainty is independent of the quantity being calculated.
Advection: Also includes AERI uncertainty

AERI thermodynamic retrievals also contain 1-sigma uncertainties.

As part of the AERI thermodynamic retrieval, the posterior covariance matrix $S$ is calculated.

The retrieved value is the statistically most likely value given the observed radiance, but other profiles are mathematically valid.

We can reconstruct other valid profiles using $S$ and the observation uncertainty.

$$\hat{\mathbf{X}} = \mathbf{S}^{1/2} \mathbf{Z} + \mathbf{X}$$
This time, both wind and water vapor mixing ratio are perturbed according to their uncertainty characteristics.

The uncertainty is driven by the uncertainty in the wind speed, which is larger during the day.
Truncation Error

Michael (1994) used idealized fields to evaluate the line integral method as a function of the number of observation points.

More points == better calculations (beyond 6 points, little change)
How to Validate? Use the HRRR

High-Resolution Rapid Refresh (HRRR) model
• National Weather Service operational model
• 3 km grid
• Hourly forecasts
• Version 2 was operational Aug 2006 to July 2018
  • Includes the LAFE period
• Version 3 operational as of July 2018
  • Better subgrid processes
  • Reduced high precip bias
  • Hybrid sigma / pressure grid

We have experimental HRRR v. 3 for LAFE period.

Note: instead of using analyses (0 hr forecasts), it’s better to use the 1 hr forecast from the previous run
• Allows the model time to cycle obs.
So, what have we learned?
1. Line integral methods remain an underexploited way to evaluate spatial derivatives from profiler data.
2. Values calculated from these methods agree in sign and magnitude with what would be expected for these quantities.
3. Validation is still necessary. Small scale operational models are a good choice.
4. Many other quantities to investigate
   • Deformation
   • Temperature advection
   • Moist flux convergence

Thank you!
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