# NATIONAL SEVERE STORMS LABORATORY

## 2003 Formal Publications by NSSL and CIMMS Scientists

Formal: 2004, 2003, 2002, 2001, 2000, 1999, 1998, 1997, 1996, 1995, 1994, 1993
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# NSSL Lead Author:

**Brooks, H. E.**, **C. A. Doswell III**, and M. P. Kay, 2003: Climatological estimates of local daily tornado probability. *Wea. Forecasting*, **18**, 626-640.

An estimate is made of the probability of an occurrence of a tornado day near any location in the contiguous 48 states for any time during the year. Gaussian smoothers in space and time have been applied to the observed record of tornado days from 1980 to 1999 to produce daily maps and annual cycles at any point on an 80 km X 80 km grid. Many aspects of this climatological estimate have been identified in previous work, but the method allows one to consider the record in several new ways. The two regions of maximum tornado days in the United States are northeastern Colorado and peninsular Florida, but there is a large region between the Appalachian and Rocky Mountains that has at least 1 day on which a tornado touches down on the grid. The annual cycle of tornado days is of particular interest. The southeastern United States, outside of Florida, faces its maximum threat in April. Farther west and north, the threat is later in the year, with the northern United States and New England facing its maximum threat in July. In addition, the repeatability of the annual cycle is much greater in the plains than farther east. By combining the region of greatest threat with the region of highest repeatability of the season, an objective definition of Tornado Alley as a region that extends from the southern Texas Panhandle through Nebraska and northeastward into eastern North Dakota and Minnesota can be provided.

**Brooks, H.**, **C. Doswell III**, D. Dowell, R. Holle, **B. Johns**, **D. Jorgensen**, **D. Schultz**, **D. Stensrud**, S. Weiss, **L. Wicker**, and **D. Zaras**, 2003: Severe thunderstorms and tornadoes. Handbook of Weather, Climate, and Water: Dynamics, Climate, Physical Meteorology, Weather Systems, and Measurements. T. D. Potter and B. R. Colman, Eds., Wiley-Interscience, 575-619.

**Brooks, H. E.**, J. W. Lee, and J. P. Craven, 2003: The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmos. Res.*, **67-68**, 73-94.

Proximity sounding analysis has long been a tool to determine environmental conditions associated with different kinds of weather events and to discriminate between them. It has been limited, necessarily, by the spatial and temporal distribution of soundings. The recent development of reanalysis datasets that cover the globe with spatial grid spacing on the order of 200 km and temporal spacing every six hours allows for the possibility of increasing the number of proximity soundings by creating "pseudo-soundings." We have used the NCAR/NCEP reanalysis system to create soundings and find environmental conditions associated with significant severe thunderstorms (hail at least 5 cm in diameter, wind gusts at least 120 km h-1, or a tornado of at least F2 damage)

and to discriminate between significant tornadic and non-tornadic thunderstorm environments in the eastern United States for the period 1997-1999. Applying the relationships from that region to Europe and the rest of the globe, we have made estimates of the frequency of favorable conditions for significant severe thunderstorms. Southern Europe has the greatest frequency of significant severe thunderstorm environments, particular over the Spanish plateau and the region east of the Adriatic Sea. Favorable significant tornadic environments are found in France and east of the Adriatic. Worldwide, favorable significant thunderstorm environments are concentrated in equatorial Africa, the central United States, southern Brazil and northern Argentina, and near the Himalayas. Tornadic environments are by far the most common in the central United States, with lesser areas in southern Brazil and northern Argentina.

**Davies-Jones, R.**, 2003: An expression for effective buoyancy in surroundings with horizontal density gradients. *J. Atmos. Sci.*, **60**, 2922-2925.

**Davies-Jones, R**., 2003: Comments on "A generalization of Bernoulli's theorem". *J. Atmos. Sci*., **60**, 2039-2041.

**Davies-Jones, R.**, 2003: Propagation of supercell updrafts. *Bull. Amer. Meteor. Soc.*, **84**, 14-15.

**Davies-Jones, R.**, 2003: Reply [to Comments on "Linear and nonlinear propagation of supercell storms" by R. Rotunno and M. L. Weisman]. *J. Atmos. Sci.*, **60**, 2420-2426.

**Doviak, R. J.**, and M. E. Frazier, **D. Doviak**, 2003: Doppler Radar in the Encyclopedia of Atmospheric Sciences. Elsevier Science Ltd., London, UK, pp 1802-1812.

**Hane, C.E.**, 2003: Quiescent and synoptically-active drylines: A comparison based upon case studies. *Meteorology and Atmospheric Physics*, 17 pp. Online at: http://www.springerlink.com/app/home/contribution.asp?wasp=h7e8jf21gk5ythea4ua0& referrer=parent&backto=issue,6,9;journal,1,24;linkingpublicationresults,1,1

**Hane, C.E.**, J.D. Watts, D. L. Andra, Jr., J. A. Haynes, E. Berry, **R. M. Rabin**, F. H. Carr, 2003: The evolution of morning convective systems over the U. S. Great Plains during the warm season. Part I: The forecast problem. *Wea. Forecasting*, **18**, 1286-1294.

The factors that influence the evolution of convective systems during the late morning over much of the Great Plains are not well understood. It is known that in this region the majority such systems dissipate or decrease in intensity during this period. With this in mind, a summary is given of comments made during the occurrence of morning convective systems by forecasters at two National Weather Service (NWS) offices relating to factors that were most important in determining their forecasts of system evolution. Additionally, results of a preliminary climatology covering eight summer months for 181 summer precipitation systems affecting the county warning areas of the two NWS offices during late morning are presented. Revealed among the significant system characteristics is that approximately two-thirds of the included systems either decreased in intensity or dissipated during the late morning.

**Jorgensen, D. P.**, Z. Pu, P. O. G. Persson, and W.-K. Tao, 2003: Variations associated with cores and gaps in a pacific narrow cold frontal rainband. *Mon. Wea. Rev.*, **131**, 2705-2729.

A NOAA P-3 instrumented aircraft observed an intense, fast-moving narrow cold frontal rainband (NCFR) as it approached the U. S. California coast on 19 February 2001 during the Pacific Coastal Jets Experiment. Airborne Doppler radar data obtained while the frontal system was well offshore indicated that a narrow ribbon of very high radar reflectivity convective cores characterized the rainband at low levels with echo tops to ~4-5 km, and pseudo-dual-Doppler analyses showed the low-level convergence of the prefrontal air. The NCFR consisted of gaps of weaker reflectivity and cores of stronger reflectivity along its length, perhaps as a result of hydrodynamic instability along its advancing leading edge. In contrast to some earlier studies of cold frontal rainbands, density current theory described well the motion of the overall front. The character of the updraft structure along the NCFR varied systematically along the length of the precipitation cores and in the gap regions. The vertical shear of the cross-frontal low-level ambient flow exerted a strong influence on the updraft character, consistent with theoretical arguments developed for squall lines describing the balance of vorticity at the leading edge. In short segments at the northern ends of the cores, the vertical wind shear was strongest with the updrafts and rain shafts more intense, narrower, and more erect or even downshear tilted. At the southern ends of the cores and just north of the gaps, the wind shear weakened with less intense updrafts that tilted upshear and contained a broader band of rainfall. Simulations using the MM5 nonhydrostatic mesoscale nested grid model are used to investigate the core and gap regions, focusing on the relationship between the character of the modeled updrafts and the balance between the cold air induced vorticity and the pre-frontal ambient shear vorticity. The cold air behind the NCFR, which forces new convection along the its leading edge, is probably maintained by large-scale advection of cold air plus evaporative cooling processes within the heavy rain region of the NCFR. Observations confirm the model results; i.e., that the updraft character depends on the balance of vorticity at the leading edge. Downshear-tilted updrafts imply that convection at the northern ends of the cores may weaken with time relative to the frontal segments at the southern ends, since inflow air would be affected by passage through the heavy rain region before ascent. A mechanism for line modification is thus implied.

**Jorgensen, D. P.**, and T. M. Weckwerth, 2003: Forcing and organization of convective systems. *Radar and Atmospheric Science: A Collection of Essays in Honor of David Atlas*, Meteor. Monogr., No. 52, Amer. Meteor. Soc., 75-103.

From its initial deployment as a research tool following the Second World War, radar has played a fundamental role in revealing the forces that initiate and organize severe storms and larger mesoscale convective systems comprised of a conglomeration of convective storm cells. Early radar observations were primarily descriptive and showed the tremendous variety of precipitating moist convection types and sizes. Examples include single convective storms, longer-lived multi-cellular storms, fast-moving squall lines, slower-moving linear and non-linear convective systems, and long-lived supercell storms. Certain modes or types of convective systems were shown to possess a variety of hazardous weather that includes very heavy rain, large hail, straight-line damaging winds, tornadoes, and lightning. It was soon recognized that the type of convective system was strongly dependent on the environment in which it was embedded. Researchers determined that two variables were particularly important in describing convective behavior: the vertical profile of the horizontal wind and potential instability of the air feeding the system (CAPE or convective available potential energy). The types of convective systems are discussed here according to their typical shear and CAPE values. In addition to the knowledge gained from observational radar studies, considerable advancement in understanding of convective system dynamics has resulted from high-resolution numerical simulations.

In addition to being a critical factor in determining the particular structure and organization that convective systems assume once convection is initiated, radar (particularly in clear-air mode) has been a leading tool in identifying forcing mechanisms for convective initiation. In particular, the role of "boundary-layer forcing" in initiating convection has received much attention in recent years. Boundary-layer circulations, which are sometimes precursors to deep convective development, are clearly observed by radar as reflectivity fine lines and/or discontinuities in Doppler velocity. Some of these mesoscale boundary-layer mechanisms for producing upward motion include horizontal convective rolls, sea-breeze circulations, drylines, gust fronts, orographic circulations (e.g., mountain-valley) and circulations resulting from horizontal inhomogeneities in surface character. Convection initiation sometimes does not occur continuously along boundaries, but only at preferred along-boundary locations. Location preferences can sometimes be identified with boundary intersections, such as colliding gust fronts, sea-breeze fronts and rolls, and drylines and rolls. It is not always clear, however, why convection forms at certain locations along boundaries and not others. It is possible that low-level waves, bores, and other features, which may not always be apparent in radar data, may also play an important role in convection initiation processes.

**Kurkowski, N. P.**, **D. J. Stensrud**, and **M. E. Baldwin**, 2003: Assessment of implementing satellite-derived land cover data in the Eta model. *Wea. Forecasting*, **18**, 404-416.

One of the challenges in land surface modeling involves specifying accurately the initial state of the land surface. Most efforts have focused upon using multi-year climatologies to specify the fractional coverage of vegetation. For example, the National Center for Environmental Prediction (NCEP) Eta model uses a five-year satellite climatology of monthly Normalized Difference Vegetation Index (NDVI) values to define the fractional vegetation coverage, or greenness, at 1/8 degree (approximately 14 km) resolution. These data are valid on the 15th of every month and are interpolated temporally for daily runs. Yet vegetation characteristics change from year-to-year and are influenced by short-lived events such as fires, crop harvesting, droughts, floods, and hailstorms that are missed using a climatological database. To explore the importance of the initial state vegetation characteristics on operational numerical weather forecasts, the response of the Eta model to initializing fractional vegetation coverage directly from the National Oceanic and Atmospheric Administration's Advanced Very High Resolution Radiometer (AVHRR) data is investigated. Numerical forecasts of the Eta Model, using both climatological and near-real-time values of fractional vegetation coverage, are compared with observations to examine the potential importance of variations in vegetation to forecasts of 2-m temperatures and dewpoint temperatures from 0 to 48 h for selected days during the 2001 growing season. Results show that use of the near-real-time vegetation fraction data improves the forecasts of both the 2-m temperature and dewpoint temperature for much of the growing season, highlighting the need for this type of information to be included in operational forecast models.

**Lewis, J.**, 2003: Ooishi's Observation: Viewed in the Context of Jet Stream Discovery. *Bull. Amer. Meteor. Soc.*, 357-369. DOI: 10.1175/BAMS-84-issue 3-357.

**Lewis, J.**, D. Koracin, **R. Rabin**, and J. Businger, 2003: Sea fog off the California Coast: Viewed in the Contest of Transient Weather Systems. *JGR (Atmospheres)*,**118**, No. D15, 4457-4474. DOI: 10.1029/2002JD002833,2003.

**Stensrud, D.J.**, **H.E. Brooks**, and S.J. Weiss, 2003: Weather prediction: Severe weather forecasting. Encyclopedia of the Atmospheric Sciences, Vol. 6, Academic Press, New York, 2568-2576.

**Stensrud, D.J.**, and **N. Yussouf**, 2003: Short-range ensemble predictions of 2-m temperature and dewpoint temperature over New England. *Mon. Wea. Rev.*, **131**, 2510-2524.

A multi-model short-range ensemble forecasting system created as part of a National Oceanic and Atmospheric Administration pilot program on temperature and air quality forecasting over New England during the summer of 2002 is evaluated. A simple 7-day running mean bias correction is applied individually to each of the 23 ensemble members. Various measures of accuracy are used to compare these bias-corrected ensemble predictions of 2-m temperature and dewpoint temperature with those available from the Nested Grid Model (NGM) Model Output Statistics (MOS). Results indicate that the bias-corrected ensemble mean prediction is as accurate as the NGM MOS for temperature predictions, and is more accurate than the NGM MOS for dewpoint temperature predictions, for the 48 days studied during the warm season. When the additional probabilistic information from the ensemble is examined, results indicate that the ensemble clearly provides value above that of NGM MOS for both variables, especially as the events become more unlikely. Results also indicate that the ensemble has some ability to predict forecast skill for temperature with a correlation between ensemble spread and the error of the ensemble mean of greater than 0.7 for some forecast periods. The use of a multi-model ensemble clearly helps to improve the spread-skill relationship.

**Wood, V. T.**, **R. A. Brown**, and **S. V. Vasiloff**, 2003: Improved detection using negative angles for mountaintop WSR-88Ds. Part II: Simulations of the Three Radars Covering Utah. *Wea. Forecasting*, **18**, 393-403

About one-third of the Weather Surveillance Radar-1988 Doppler (WSR-88D) radars located in the western third of the United States are on the tops of mountains. These mountaintop radars employ scanning strategies that were designed for flatland radars, with the lowest elevation angle being +0.5°. Consequently, the radar signals are sent well above the populace and terrain surrounding the radar. The inability to adequately detect low-altitude weather events results in missed warnings of severe weather and in underestimates of the amount and areal extent of

precipitation. Mountaintop radars could be utilized much more effectively if the scanning strategies included negative elevation angles. The state of Utah has the disadvantage that all three of the WSR-88Ds used by the National Weather Service to monitor weather events in the state are located on the tops of mountains. To determine the extent to which negative elevation angles would improve the detection capabilities of these radars over Utah and portions of the adjacent states, a WSR-88D simulation model is used to compare the existing scanning strategies with those that incorporate negative elevation angles. As might be expected, the use of negative elevation angles enhances low- to midaltitude detection of weather events over a much larger area than is possible using the existing scanning strategies. For example, the area where the centers of the beams from the three radars currently are within 1 km of the ground encompasses only 2% of the area within 230 km of the radars. Using negative elevation angles, the areal coverage within 1 km of the ground increases to over 30%.

**Wood, V. T.**, **R. A. Brown**, **S. V. Vasiloff**, 2003: Negative elevation angles for mountaintop radar. *Bull. Amer. Soc.,* **84**, 996-997.

**Xu, Q.**, 2003: Nearly symmetric and nearly baroclinic instabilities in the presence of diffusivity. Part I: Growth rate patterns. J. Fluid Mech. 492, 181-205.

Computations are performed to examine the instabilities of baroclinically sheared Eady basic flows with respect to banded normal-mode perturbations in three-dimensional space in the presence of eddy diffusivity with two (free-slip and non-slip) types of boundary conditions. The nondimensional model system contains four external parameters: the Richardson number, the Ekman number, the Prandtl number and the ratio between inertial and buoyancy frequencies. The solutions are controlled mainly by the first three parameters. Growth rate patterns are computed for unstable modes as functions of the horizontal wavelength, l, and tilt angle, a, of the band orientation with respect to the basic shear (measured negative clockwise from the basic-shear direction). It is found that the main growth rate pattern (for non-propagating modes with respect to the middle-level basic flow) has only one maximum unless the Ekman number is sufficiently small. The growth rate pattern obtained with the free-slip boundary conditions has a slightly larger global maximum and is more symmetric with respect to the symmetric axis in the space of (l, a) than that obtained with the non-slip boundary conditions. When the Richardson number increases from 0.25 to 1.0, the maximum growth rate decreases and the associated instability changes gradually from a nearly symmetric type to a nearly baroclinic type as manifested by the continuous increase of l (from mesoscale to synoptic scale) and continuous change of a (from nearly zero to nearly -90o).

When the Ekman number is sufficiently small, the main growth rate pattern can have two local maxima if the Richardson number is in a subrange within $0.8 < Ri < 1.0$. One of the local maxima is near the symmetric axis and the other is near the baroclinic axis in the wavenumber space. When the Richardson number increases through a transitional value in the subrange, the global maximum growth rate decreases continuously but the maximum point jumps from one local maximum to the other and the associated instability switches from a nearly symmetric type to a nearly Eady-baroclinic type. The subrange depends on the smallness of the Ekman number and it diminishes as the Ekman number increases to 0.0025 (for the non-slip case). The computed growth rates and (l, a) are compared with the nearly inviscid results of Miller and Antar and the inviscid results of Stone.

**Xu, Q.**, and J. Gong, 2003: Background error covariance functions for Doppler radial-wind analysis. *Quart. J. Roy. Meteor. Soc.*, **129**, 1703-1720.

Under the assumption that the vector field of the background wind error is Gaussian random, homogeneous and isotropic in the horizontal, a two-dimensional form of error covariance function is derived for the radial component of the background vector wind projected onto the direction of radar beam at a low elevation. The derived covariance function is homogeneous but nonisotropic in the horizontal or, approximately, on the conic surface of low-elevation radar scans. This covariance function can be directly applied to statistical interpolation of radar observed radial winds on the conic surface, although the true optimality of the analysis depends on the underlying assumption. It can be also used as an influence function for the radial-wind analysis of with zero background. The structure of this covariance function is interpreted in terms of the influence of a single-point observation to the radial-wind analysis. The utility of this covariance function is demonstrated by numerical experiments. The results show that using the derived error covariance function improves the analysis in data void areas especially in the vicinity of the radar.

**Xu, Q.**, and B. Zhou, 2003: Retrieving soil moisture from soil temperature measurements by using linear regression. *Adv. Atmos. Sci.*, **20**, 849-858.

> A simple linear-regression method is developed to retrieve daily averaged soil water content from diurnal variations of soil temperature measured at three or more depths. The method is applied to Oklahoma Mesonet soil temperature data collected at the depths of 5, 10 and 30 cm during 11-20 June 1995. The retrieved bulk soil water contents are compared with direct measurements for one pair of nearly collocated Mesonet and ARM stations and also compared with the retrievals of a previous method at 14 enhanced Oklahoma Mesonet stations. The results show that the current method gives more persistent retrievals than the previous method. The method is also applied to Oklahoma Mesonet soil temperature data collected at the depths of 5, 25, 60, and 75 cm from the Norman site during 20-30 July 1998 and 1-31 July 2000. The retrieved soil water contents are verified by collocated soil water content measurements with rms differences smaller than the soil water observation error (0.05 m3m-3). The retrievals are found to be moderately sensitive to random errors (±0.1 K) in the soil temperature observations and errors in the soil type specifications.

# CIMMS Lead Author:

**Baldwin, M. E.** and S. Lakshmivarahan, 2003: Spatial characterization of rainfall patterns for use in a classification system. *Intelligent Engineering Systems Through Artificial Neural Networks*, 13, C. H. Dagli, A. L Buczak, J. Ghosh, M. J. Embrechts, and O. Ersoy Eds, ASME Press, 683-688.

**Gourley, J.J.** and **C.M. Calvert**, 2003: Automated detection of the bright band using WSR-88D radar data. *Wea. Forecasting*, **18**, 585-599.

**Gourley, J.J.** and B.E. Vieux, 2003: The effects of radar-derived rainfall uncertainties on forecasts from a distributed hydrologic model. Weather Radar Information and Distributed Hydrological Modelling, *Intl. Assoc. of Hydro. Sci. Publ.* no. **282**, 130-137.

**Ivic, R.I.**, **D.S. Zrnic**, and **S. M. Torres**, 2003: Whitening in range to improve weather radar spectral moment estimates. Part II: Experimental evaluation. *J. Atmos. Oceanic Technol.*, **20**, 1449-1459.

> Demonstration of a method for improved Doppler spectral moment estimation is made on NOAA's research and development Weather Surveillance Radar-1988 Doppler (WSR-88D) in Norman, Oklahoma. Time series data have been recorded using a commercial processor and digital receiver whereby the sampling frequency is several times larger than the reciprocal of the transmitted pulse width. The in-phase and quadrature-phase components of oversampled weather signals are used to estimate the first three spectral moments by suitably combining weighted averages in range with usual processing at fixed range locations. The weights are chosen in such a manner that the resulting signals become uncorrelated. Consequently, the variance of estimates decreases significantly as is verified by this experiment.

**Kain, J.S.**, **M.E. Baldwin**, S. J. Weiss, 2003: Parameterized Updraft Mass Flux as a Predictor of Convective Intensity. *Weather and Forecasting*. Vol. **18**, No. 1, 106–116.

**Kain, J. S.**, **M. E. Baldwin**, and S. J. Weiss, P. R. Janish, M. P. Kay, and G. Carbin, 2003: Subjective verification of numerical models as a component of a broader interaction between research and operations. *Wea. Forecasting*, **18**, 847-860.

**Kain, J. S.**, P. R. Janish, S. J. Weiss, **M. E. Baldwin**, R. S. Schneider, and **H. E. Brooks**, 2003: Collaboration between forecasters and research scientists at the NSSL and SPC: The Spring Program. *Bull. Amer. Meteor. Soc.*, **84**, 1797-1806.

**Lakshmanan, V.**, **R. Rabin**, and V. DeBrunner, 2003: Multiscale storm identification and forecast. *J. Atmospheric Research*, 367-380.

**Melnikov, V.M.**, **D.S. Zrnic**, **R.J. Doviak**, and **J.K. Carter**, 2003: Calibration and performance analysis of NSSL's polarimetric WSR-88D. NSSL report, 77 pp.

**Rasmussen, E. N.**, 2003: Refined supercell and tornado forecast parameters. *Wea. Forecasting*, **18**, 530-535.

This note updates a previous study that utilized a baseline climatology of soundings associated with large hail, significant tornadoes, and 10 or more cloud-to-ground lightning flashes from 1992. Expanding on the earlier analysis, it is shown that three modified forecast parameters have more value in distinguishing between environments that favor significant tornadoes and those that favor large hail but no significant tornadoes, in the climatological data. These parameters are storm-relative helicity in the 0-1 km layer adjacent to the ground, energy-helicity index computed from this measure of helicity, and the convective available potential energy that accrues from the surface to 3 km above ground level. In addition, this note provides caveats regarding the interpretation of the climatological findings.

**Rasmussen, E. N.**, **R. Davies-Jones**, and R. L. Holle, 2003: Terrestial photogrammetry of weather images acquired in uncontrolled circumstances. *J. Atmos Oceanic. Technol.*, **20**, 1790-1803.

This paper describes an accurate automated technique of terrestrial photogrammetry that is applied to weather images obtained in uncontrolled circumstances such as unknown focal length and 3-D camera orientation (azimuth and tilt of the optical axis, and roll about this axis), principal point unmarked on the image, and undetermined lens horizon. With the possible exception of the principal point, these quantities are deduced by a rapid computer algorithm with input consisting of accurate azimuth and elevation angles of landmarks that appear in the image. The algorithm works for wide-angle as well as for telephoto images and is more accurate than previous methods, which are based on assumptions of small angles and zero roll. Results are insensitive to the exact position of the principal point for telephoto images. For wide-angle photography, the principal point can be determined only if there is a sufficient number of accurately measured landmarks with diverse azimuth and elevation angles. If all the landmarks have low elevation angles, the principal point is impossible to determine and must be assumed to lie at the intersection of the diagonals of the uncropped image. The algorithm also provides the azimuth and elevation angle of any object, given the position of its image in the photograph.

A photogrammetric search technique is described for finding an entity, which is visible in one camera's photography, in the simultaneous image obtained from a different direction by a second camera. Once the same object has been identified in both images, its 3-D position is determined by triangulation.

**Ryzhkov A.V.**, **S. Giangrande**, and **T. Schuur**, 2003: Rainfall measurements with the polarimetric WSR-88D radar. NSSL report, 98 pp.

**Schultz, D. M.**, and F. Sanders, 2002: Upper-level frontogenesis associated with the birth of mobile troughs in northwesterly flow. *Mon. Wea. Rev.*, **130**, 2593-2610.

**Schultz, D. M.**, and **R. J. Trapp**, 2003: Nonclassical cold-frontal structure caused by dry subcloud air in northern Utah during the Intermountain Precipitation Experiment (IPEX). *Mon. Wea. Rev.*, **131**, 2222-2246.

The purpose of the Intermountain Precipitation Experiment (IPEX) is to improve understanding of precipitating

systems in the Intermountain West. Instrumentation deployed during the field phase of IPEX sampled a strong cold front and associated convection that moved through northern Utah on 14-15 February 2000. The surface cold front was characterized by a sharp temperature drop (8 deg C in 8 minutes), strong pressure rise (3 hPa in 30 minutes), and gusts to 40 m -1. The temperature drop at high-elevation surface stations (2500-3000 m MSL) preceded the temperature drop at low-elevation surface stations (1290-2000 m MSL) by as much as an hour, implying a forward- or downshear-tilting frontal structure. Consistent with the cooling aloft, a hydrostatic pressure rise and wind shift preceded the temperature drop at the surface. Radar captured the rapid evolution of the wind shift line into a gravity current. A forward-sloping cloud with mammatus and a 20-hPa deep superadiabatic layer underneath were observed by radar and radiosondes, respectively. Shading from this forward-sloping cloud is believed to have produced a surface-based prefrontal inversion upon which a solitary gravity wave traveled. These and other observations reveal that the forward-sloping cloud generated by a shortwave trough aloft was producing precipitation that sublimated, melted, and evaporated in the dry subcloud air (dewpoint depression of 5-10 deg C), causing the cooling aloft and the nonclassical frontal structure.

Although the storm-total precipitation associated with this system was generally light (less than 20 mm at all observing sites), the amount of precipitation was strongly a function of elevation. During one 6-h period, precipitation at stations above cloud base (roughly 2000 m MSL) varied widely, mostly due to orographic effects, although precipitation amounts at most stations were about 7-11 mm. In contrast, precipitation amounts decreased with distance below cloud base, consistent with sublimation and evaporation in the dry subcloud air.

**Schuur T.**, **A. Ryzhkov**, **P. Heinselman**, **D. Zrnic**, **D. Burgess**, and **K. Scharfenberg**, 2003: Observations and classification of echoes with the polarimetric WSR-88D radar. NSSL report, 46 pp.

**Schuur, T.J.**, **P. Heinselman**, **K. Scharfenberg**, **A. Ryzhkov**, **D. Zrnic**, **V. Melnikov**, and **J. Krause**, 2003: Overview of the Joint Polarization Experiment (JPOLE). NSSL report, 39 pp.

**Spencer, P.L.**, **D.J. Stensrud**, and J.M. Fritsch, 2003: A method for improved analyses of scalars and their derivatives. *Mon. Wea. Rev.*, **131**, 2555-2576.

Analytic observations are used to compare the traditional and triangle methods for the objective analysis of scalar variables. The traditional method for objective analysis assigns gridpoint values based on the distance from the gridpoints to each member of the set of observations. Spatial derivatives subsequently are derived by applying a finite differencing scheme to the field of gridded observations. The triangle method for objective analysis calculates the spatial first-order derivatives directly from each set of non-overlapping triangles that are formed by the observations, and the derivatives are assigned to the triangle centroids. By calculating the first-order derivatives directly from the observations, the triangle method bypasses the need for finite differencing. Triangle centroid estimates of the scalar field itself are simply arithmetic averages of the three observations comprising each triangle. The centroid estimates of the scalar variable and its spatial derivatives are then treated as observations and mapped to a uniform grid via the traditional method.

Results indicate that the traditional method for the analysis of a scalar variable is superior to the triangle method for scalar analysis because the simple averaging involved in creating the triangle centroid estimates of the scalar exposes the triangle analysis to the potential for significant damping of the input field. Indeed, although the patterns of the scalar analyses from the two methods are comparable, the analysis from the triangle method does not reproduce the amplitude of the scalar field as well as the analysis from the traditional method. Gradient and Laplacian fields computed from the triangle method, however, generally are superior to those derived by the traditional method, which tends to force all of the gradient information into the gaps between observing stations.

To overcome the deficiency of the triangle method's ability to produce an acceptable scalar analysis and the deficiency of the traditional method's ability to produce an acceptable derivative analysis, a variational objective analysis scheme is developed that combines the best aspect of the triangle method with that of the traditional method. Analyses of the scalar and its spatial derivatives from the variational analysis scheme generally are superior to analyses from both the traditional and triangle methods.

**Stumpf, G. J.**, **T. M. Smith**, and C. Thomas, 2003: The National Severe Storms Laboratory's contribution to severe weather warning improvement: Multiple-sensor severe weather applications. *Atmos. Research*, **66**, 657-669.

The National Severe Storms Laboratory (NSSL) has played the primary role in the development and evaluation of U. S. National Weather Service (NWS) severe weather applications for the Weather Surveillance Radar ú 1988 Doppler (WSR-88D). NSSL developed many of the primary detection algorithms for the radar, and is currently developing improvements to these algorithms. The traditional WSR-88D severe weather algorithms have been designed for use with a single-radar data source. Although the algorithm guidance has led to an improvement of the NWS severe weather warning statistics, it is understood that effective warning decisions can only be made via the integration of information from many sources, including input from multiple remote sensors (multiple radars, mesoscale models, satellite, lightning, etc.). Therefore, these traditional single-radar severe weather algorithms have been updated to take advantage of additional data sources in order to reduce the uncertainty of the measurements and increase the accuracy of the diagnoses of severe weather.

The NSSL Warning Decision Support System ú Integrated Information (WDSS-II) has provided an invaluable development environment to facilitate the development of these new applications. In just one year (2002), NSSL has converted its suite of single-radar severe weather detection algorithms to operate using multiple radars. NSSL has also developed a host of new radar diagnostic derivatives, including high-resolution gridded fields of vertically integrated liquid (VIL), Probability of Severe Hail, Maximum Expected Hail Size, Velocity-Derived Rotation, and Velocity-Derived Divergence. Time-integrated gridded fields of some of the above have also been developed, including hail swath information (maximum size and hail damage potential) and velocity-derived rotation tracks.

**Torres, S.M.**, and **D.S. Zrnic**, 2003: Whitening in range to improve weather radar spectral moment estimates. Part I: Formulation and simulation. *J. Atmos. Oceanic Technol.*, **20**, 1443-1448.

A method for estimation of spectral moments on pulsed weather radars is presented. This scheme operates on oversampled echoes in range; that is, samples of in-phase and quadrature phase components are collected at a rate several times larger than the reciprocal of the transmitted pulse length. The spectral moments are estimated by suitably combining weighted averages of these oversampled signals in range with usual processing of samples (spaced at the pulse repetition time) at a fixed range location. The weights in range are derived from a whitening transformation, hence, the oversampled signals become uncorrelated and consequently the variance of the estimates decreases significantly. Because the estimate errors are inversely proportional to the volume scanning times, it follows that storms can be surveyed much faster than is possible with current processing methods, or equivalently, for the current volume scanning time, accuracy of the estimates can be greatly improved. This significant improvement is achievable at large signal-to-noise ratios.

**Torres, S.M.**, and **D.S. Zrnic**, 2003: Whitening of signals in range to improve estimates of polarimetric variables. *J. Atmos. Oceanic Technol.*, **20**, 1776-1789.

Demonstration of a method for improved Doppler spectral-moment estimation is made on the NOAA's research and development WSR-88D in Norman, Oklahoma. Time series data have been recorded using a commercial processor and digital receiver whereby the sampling frequency is several times larger than the reciprocal of the transmitted pulse width. The in-phase and quadrature-phase components of oversampled weather signals are used to estimate the first three spectral moments by suitably combining weighted averages in range with usual processing at fixed range locations. The weights are chosen in such a manner that the resulting signals become uncorrelated. Consequently, the variance of estimates decreases significantly as is verified by this experiment.

**Trapp, R. J.**, and M. L. Weisman, 2003: Low-level mesovortices within squall lines and bow echoes. Part II: Their genesis and implications. *Mon. Wea. Rev.*, **131**, 2804-2823.

This two-part study proposes a fundamental explanation of the genesis, structure, and implications of lowlevel,

meso- g-scale vortices within quasi-linear convective systems (QLCSs) such as squall lines and bow echoes. Such "mesovortices" are observed frequently, at times in association with tornadoes. Idealized experiments with a numerical cloud model show that significant low-level mesovortices develop in simulated QLCSs, especially when the environmental vertical wind shear is above a minimum threshold and when the Coriolis forcing is nonzero. As illustrated by a QLCS simulated in an environment of moderate vertical wind shear, mesovortexgenesis is initiated at low levels by the tilting, in downdrafts, of initially crosswise horizontal baroclinic vorticity. Over a 30-min period, the resultant vortex couplet gives way to a dominant cyclonic vortex as the relative and, more notably, planetary vorticity is stretched vertically; hence, the Coriolis force plays a direct role in the low-level mesovortexgenesis. A downward-directed vertical pressure-gradient force is subsequently induced within the mesovortices, effectively segmenting the previously (nearly) continuous convective line. In moderate-to-strong environmental shear, the simulated QLCSs evolve into bow echoes with "straight line" surface winds found at the bow-echo apex and additionally in association with, and in fact induced by, the lowlevel mesovortices. Indeed, the mesovortex winds tend to be stronger, more damaging, and expand in area with time owing to a mesovortex amalgamation or "upscale" vortex growth. In weaker environmental shear - in which significant low-level mesovortices tend not to form - damaging surface winds are driven by a rear-inflow jet that descends and spreads laterally at the ground, well behind the gust front.

# NSSL or CIMMS Secondary Author:

Bousquet, O., **Smull, B. F.**, 2003: Airflow and Precipitation Fields within Deep Alpine Valleys Observed by Airborne Doppler Radar. *Journal of Applied Meteorology*, **42(10)**, 1497-1513.

Colle, B. A., **Smull, B. F.**, Yang, M., 2002: Numerical Simulations of a Landfalling Cold Front Observed during COAST: Rapid Evolution and Responsible Mechanisms. *Monthly Weather Review*, **130**(8), 1945-1966.

Deng, A., N. L. Seaman and **J. S. Kain**, 2003: A shallow-convection parameterization for mesoscale models Part I: Sub-model description and preliminary applications. *J. Atmos. Sci.*, **60**, 34-56.

Deng, A., N. L. Seaman and **J. S. Kain**, 2003: A shallow-convection parameterization for mesoscale models Part II: Verification and sensitivity studies. *J. Atmos. Sci.*, **60**, 57-78.

Dotzek, N., J. Grieser, and **H. E. Brooks**, 2003: Statistical modeling of tornado intensity distributions, *Atmos. Res.*, **67-68**, 163-187.

We address the issue to determine an appropriate general functional shape of observed tornado intensity distributions. Recently, it was suggested that in the limit of long and large tornado records, exponential distributions over all positive Fujita or TORRO scale classes would result. Yet, our analysis shows that even for large databases observations contradict the validity of exponential distributions for weak (F0) and violent (F5) tornadoes. We show that observed tornado intensities can be much better described by Weibull distributions, for which an exponential remains a special case. Weibull fits in either v or F scale reproduce the observations significantly better than exponentials. In addition, we suggest to apply the original definition of negative intensity scales down to F-2 and T-4 (corresponding to v=0 m s-1) at least for climatological analyses. Weibull distributions allow for an improved risk assessment of violent tornadoes up to F6, and better estimates of total tornado occurrence, degree of underreporting and existence of subcritical tornadic circulations below damaging intensity. Therefore, our results are relevant for climatologists and risk assessment managers alike.

Ebert, E. E., U. Damrath, W. Wergen, and **M. E. Baldwin**, 2003: The WGNE assessment of short-term quantitative precipitation forecasts. *Bulletin of the American Meteorological Society*, **84**, 481-492.

Gong, J., L. Wang, and **Q. Xu**, 2003: A three-step dealiasing method for Doppler velocity data quality control. *J. Atmos. & Oceanic Technology*, **20**, 1738-1748.

A three-step method is developed for Doppler radar velocity dealiasing. First, the modified VAD method of Tabary et al. is adopted and applied to raw (aliased) velocity data to estimate horizontal vector velocities averaged on selected circles of radar scans. These velocities are used as preliminary references to detect and pre-dealiase or flag (if not correctable) possible alias errors. Then, the traditional VAD method is applied to the pre-dealiased velocity data to produce refined reference velocities to further detect and dealiase or flag alias errors in the second step. After these two steps, flagged data points are confined in small areas (often associated with strong shear and/or convergence flows), so the dealiased velocities along the boundary of each small area provide reliable starting points for the continuity check in the third step. Two-dimensional continuity check can start from any and every boundary point and proceed inward until all the flagged data are checked within each small area. The method is tested with Doppler radar data collected during the 3 May 1999 Oklahoma tornado outbreak - a difficult case for dealiasing. The results show that the method is efficient and effective even in the areas of mesocyclones.

Higgins, R.W., A. Douglas, A. Hahmann, E.H. Berbery, D. Gutzler, J. Shuttleworth, **D. Stensrud**, J. Amador, R. Carbone, M. Cortez, **M. Douglas**, R. Lobato, **J. Meitin**, C. Ropelewski, J. Schemm, S. Schubert, and C. Zhang, 2003: Progress in Pan American CLIVAR research: The North American monsoon system. Atmosphera, 16, 29-65.

The overall goal of Pan American CLIVAR Research on the North American Monsoon System is to determine the sources and limits of predictability of warm season precipitation over North America, with emphasis on time scales ranging up to seasonal-to-interannual. To achieve this goal, several research objectives have been identified including (1) a better understanding of the key components of the monsoon system and their temporal and spatial variability, (2) a better understanding of the role of this system within the global water cycle, (3) improved observational data sets, and (4) improved simulation and monthly-to-seasonal prediction of the monsoon and regional water resources. The purpose of this paper is to review the recent progress made towards achieving these objectives and to highlight some of the future challenges based on gaps in our understanding.

Homar, V., R. Romero, **D.J. Stensrud**, C. Ramis, and S. Alonso, 2003: Numerical diagnosis of a small, quasi-tropical cyclone over the western Mediterranean: Dynamical vs. boundary factors. *Quart. J. Roy. Meteor. Soc.*, **129**, 1469-1490.

A small, quasi-tropical cyclone occurred on 12 September 1996 over the western Mediterranean. Intense convective activity over the region during this period also produced a tornado outbreak in the Balearic Islands and torrential precipitation over eastern mainland Spain.

Mesoscale model runs properly simulate the cyclone formation and show convection and heavy precipitation following the cyclone trajectory during its eastward progression. A sensitivity study examining the upper-level dynamic forcing, latent- and sensible-heat fluxes from the sea, and orography is conducted. A potential-vorticity (PV) inversion technique is used to reduce the amplitude of the upper-level trough in the model initial conditions. The results show that neither the orography nor the sensible-heat flux from the sea play a significant role during this particular cyclone development. Conversely, both the latent-heat flux and the upper-level trough are shown to be crucial for low-level cyclogenesis. Features common to hurricane-like polar lows are found for the cyclone, and an analysis of the precise role of the upper-level structures and convective development is conducted.

A factor-separation technique is used to determine the individual effects of the aforementioned factors, as well as their interaction. At the first stage of the cyclogenesis, the upper-level PV anomaly enhanced the low-level circulation of the synoptic-scale low and enhanced the latent-heat flux from the sea. During its mature stage, the circulation associated with the small-scale cyclone enhanced the latent-heat flux from the sea, therby helping to maintain the development of deep convection, and inducing further cyclone deepening by diabatic heating. This scenario has many similarities with the air-sea interaction instability mechanism. Thus, the joint action of the upper-level anomaly, as a spin-up agent, and the latent-heat flux, as a sustainer of convection, emerges as the primary factor for the genesis and evolution of the small quasi-tropical cyclone.

Markowski, P. M., J. M. Straka, and **E. N. Rasmussen**, 2003: Tornadogenesis resulting from the transport of circulation by a downdraft: Idealized numerical simulations. *J. Atmos. Sci.*, **60**, 795-823.

Marshall, C.H. Jr., K.C. Crawford, K.E. Mitchell, and **D.J. Stensrud**, 2003: The impact of the land surface physics in the operational NCEP Eta Model on simulating the diurnal cycle: Evaluation and testing using Oklahoma Mesonet data. *Wea. Forecasting*, **18**, 748-768.

On 31 January 1996, the National Centers for Environmental Prediction/Environmental Modeling Center (NCEP/EMC) implemented a state-of-the-art land surface parameterization in the operational Eta Model. The purpose of this study is to evaluate and test its performance and demonstrate its impacts on the diurnal cycle of the modeled planetary boundary layer (PBL). Operational Eta Model output from summer 1997 are evaluated against the unique observations of near-surface and subsurface fields provided by the Oklahoma Mesonet. The evaluation is partially extended to July 1998 to examine the effects of significant changes that were made to the operational model configuration during the intervening time.

Results indicate a severe positive bias in top-layer soil moisture, which was significantly reduced in 1998 by a change in the initialization technique. Net radiation was overestimated, largely because of a positive bias in the downward shortwave component. Also, the ground heat flux was severely underestimated. Given energy balance constraints, the combination of these two factors resulted in too much available energy for the turbulent fluxes of sensible and latent heat. Comparison of model and observed vertical thermodynamic profiles demonstrates that these errors had a marked impact on the model PBL throughout its entire depth. Evidence also is presented that suggests a systematic underestimation of the downward entrainment of relatively warmer, drier air at the top of the PBL during daylight hours.

Analyses of the monthly mean bias of 2-m temperature and specific humidity revealed a cool, moist bias over western Oklahoma, and a warm, dry bias over the eastern portion of the state. A very sharp transition existed across central Oklahoma between these two regimes. The sharp spatial gradient in both the air temperature and humidity bias fields is strikingly correlated with a sharp westúeast gradient in the model vegetation greenness database. This result suggests too much (too little) latent heat flux over less (more) vegetated areas of the model domain.

A series of sensitivity tests are presented that were designed to explore the reasons for the documented error in the simulated surface fluxes. These tests have been used as supporting evidence for changes in the operational model. Specifically, an alternative specification for the soil thermal conductivity yields a more realistic ground heat flux. Also, the alternative thermal conductivity, when combined with a slight adjustment to the thermal roughness length, yields much better internal consistency among the simulated skin temperature and surface fluxes, and better agreement with observations.

Keenan, T., P. Joe, J. Wilson, C. Collier, B. Golding, **D. Burgess**, P. May, C. Pierce, J. Bally, A. Crook, A. Seed, D. Sills, L. Berry, R. Potts, I. Bell, N. Fox, E. Ebert, M. Eilts, K. O'Loughlin, R. Webb, R. Carbone, K. Browning, R. Roberts, and C. Mueller, 2003: The Syndey 2000 World Weather Research Programme Forecast Demonstration Project: Overview and current status. *Bull Amer Meteor Soc*, **84**, 1041-1054.

Lakshmivarahan, S., Y. Honda, and **J. Lewis**, 2003: Second-order approximation to the 3DVAR cost function: application to analysis/forecast. *Tellus*, **55A**, 371-384.

McPherson, R.A., **D.J. Stensrud**, and K.C. Crawford, 2004: The impact of Oklahoma's winter wheat belt on the mesoscale environment. *Mon. Wea. Rev.*, **132**, 405-421.

Oklahoma Mesonet data were used to measure the impact of Oklahoma's winter wheat belt on the mesoscale environment from 1994 to 2001. Statistical analyses of monthly means of near-surface air temperatures demonstrated that 1) a well-defined cool anomaly existed across the wheat belt during November, December,

January, February, and April, and 2) a well-defined warm anomaly existed across the wheat belt during June, July, and August. Data from crop year 2000 indicated a slight moist anomaly over the growing wheat from November 1999 through April 2000. In addition, based upon 21 000 daily statistics over eight unique years, statistical computations indicated less than a 0.1% chance that the moist anomaly during March resulted from random chance.

During the period from 1999 to 2001, about 50 days between 15 March and 1 May showed evidence of heightened values of daily maximum dewpoint over Oklahoma's winter wheat belt as compared to adjacent grasslands. On more than half of these days, the dewpoint was enhanced only across five or six counties in north-central Oklahoma, where the winter wheat production was the largest. Another 90 days between 1 June and 31 July revealed a distinct warm anomaly in daily maximum air temperatures over the wheat belt, particularly across north-central Oklahoma.

These analyses demonstrate that Oklahoma's winter wheat belt has a dramatic impact on the near-surface, mesoscale environment during its growth and after its harvest. Consequently, it is imperative that mesoscale forecasts, whether produced objectively or subjectively, account for the vegetationúair interactions that occur across western Oklahoma and, presumably, across other crop regions in the United States and around the globe.

Rasmussen, R., M. Dixon, **S. Vasiloff**, F. Hage, S. Knight, J. Vivekanandan, and M. Xu, 2003: Snow nowcasting using real-time correlation of radar reflectivity with snow gauge accumulation. *J. Appl. Meteor.*, **42**, 20-36.

Roebber, P. J., S. L. Bruening, **D. M. Schultz**, and **J. V. Cortinas Jr.**, 2003: Improving snowfall forecasting by diagnosing snow density. *Wea. Forecasting*, **18**, 264-287.

Setv3k, M., R.M. Rabin, C.A. Doswell III, V. Levizzani, 2003: Satellite observations of convective storm top features in the 1.6 and 3.7/3.9 m spectral bands. *Atmospheric Research*, Vols. **67-68**, 607-627.

Sills, D. M., J. Wilson, P. Joe, **D. Burgess**, R. Webb, and N. Fox, 2004: The 3 November tornadic event during Syndey 2000: Storm evolution and the role of low-level boundaries. *Wea. Forecasting*, **19**, 22-42.

Stoelinga, M. T., Hobbs, P. V., Mass, C. F., Locatelli, J. D., Colle, B. A., Houze, R. A., Rangno, A. L., Bond, N.A., **Smull, B. F.**, Rasmussen, R. M., Thompson, G., Colman, B. R. 2003: Improvement of Microphysical Parameterization through Observational Verification Experiment. *Bulletin of the American Meteorological Society*, **84(12)**, 1807-1826.

Weisman, M. L., and **R. J. Trapp**, 2003: Low-level mesovortices within squall lines and bow echoes. Part I: Overview and dependence on environmental shear. *Mon. Wea. Rev.*, **131**, 2779-2803.

This two-part study proposes fundamental explanations of the genesis, structure, and implications of lowlevel meso- g-scale vortices within quasi-linear convective systems (QLCSs) such as squall lines and bow echoes. Such "mesovortices" are observed frequently, at times in association with tornadoes. Idealized simulations are used herein to study the structure and evolution of meso- g-scale surface vortices within QLCSs and their dependence on the environmental vertical wind shear.Within such simulations, significant cyclonic surface vortices are readily produced when the unidirectional shear magnitude is 20 m $s^{-1}$ or greater over a 02.5- or 05-km-AGL layer. As similarly found in observations of QLCSs, these surface vortices form primarily north of the apex of the individual embedded bowing segments as well as north of the apex of the larger-scale bow-shaped system. They generally develop first near the surface but can build upward to 68 km AGL. Vortex longevity can be several hours, far longer than individual convective cells within the QLCS; during this time, vortex merger and upscale growth is common. It is also noted that such mesoscale vortices may be responsible for the production of extensive areas of extreme "straight line" wind damage, as has also been observed with some QLCSs. Surface vortices are also produced for weaker shears but remain shallow, weak, and short-lived.

Although similar in size and strength to mesocyclones associated with supercell storms, and also sometimes producing similar hooklike structures in the rain field, it is also shown that the present vortices are quite distinct, structurally and dynamically. Most critically, such vortices are not associated with long-lived, rotating updrafts at midlevels and the associated strong, dynamically forced vertical accelerations, as occur within supercell mesocyclones.

Zhang, G., **R. J. Doviak**, J. Vivekanandan, W. O. J. Brown, and S. A. Cohn, 2003: Cross-correlation ratio method to estimate cross beam-wind and comparison with a full correlation analysis. *Radio Science*, **38(3)**, 8052, doi:10.1029/2002RS002682, 2003.

Zhang, G., **R. J. Doviak**, J. Vivekanandan, and Tian-You Yu, 2003: Angular and range interferometry to measure wind. *Radio Science*, **38(6)**, 1106, doi:10.1029/2003RS002927.

Radial wind is routinely measured by Doppler method, whereas winds transverse to the radar beam are measured using an interferometric technique in which three or more spaced antennas are used (i.e., the Spaced Antenna (SA) technique). In this paper, an interferometric technique is examined whereby a single antenna is used to measure both radial and transverse winds. Angular Interferometry (AI) determines transverse wind, and Range Interferometry (RI) determines radial wind. The cross-correlation of signals, received from different angles and from different ranges by a single antenna, is derived based on wave scattering from random fluctuations of refractive index. The radial and transverse wind components are estimated from the cross-correlation of signals received from different ranges and different directions. The theoretical standard deviation of the estimated wind is derived, and its dependence on spatial resolution, observation time, and turbulence is presented. The theory shows that AI requires small beam size to measure transverse wind accurately, contrary to the SA technique, whereas RI requires fine range resolution to perform well.