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Generation of Synthetic Satellite Data with OMEGA

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ABSTRACT

Satellite data retrieval algorithms almost always involve a large degree of model or simulation input. As an example, the satellite might provide a radiance or transmittance measurement that has to be unfolded to provide temperature or mass density. In order to convert transmittance into mass density, the operator must make some assumptions on the mass extinction coefficient and particle size distribution (PSD). These assumptions are often based upon climatological averages or upon simulation results.

The Operational Multiscale Environment model with Grid Adaptivity (OMEGA) is a new atmospheric simulation system that merges state-of-the-art computational fluid dynamics techniques with a comprehensive non-hydrostatic equation set that includes both explicit and parameterized microphysics. OMEGA is based upon an unstructured triangular prism grid that permits a horizontal grid resolution ranging from 100 km down to 1 km and a vertical resolution from a few tens of meters in the boundary layer to 1 km in the free troposphere. OMEGA also contains an **embedded** aerosol transport algorithm that permits the simulation at high resolution of the transport and diffusion of either grid based aerosols or of Lagrangian parcels.

OMEGA represents a significant advance in the field of weather prediction and aerosol transport. Current operational forecast models are scale-specific and have a limit to their resolution caused by their fixed rectangular grid structure. OMEGA, on the other hand, is naturally scale spanning and its unstructured grid permits the addition of grid elements at any point in space and time. This means that OMEGA can readily adapt its grid to fixed surface or terrain features, or dynamic features in the evolving weather. This feature also makes OMEGA a useful tool for satellite data retrieval and for the generation of synthetic satellite data.

Synthetic satellite data is generated by recognizing that it is easier, in some ways, to simulate the performance of a sensor using the simulated environment and the sensor characteristics than to extract environmental information from the sensor data. This technique has been applied to generate simulated radar data as well as to produce a simulated photograph of an isolated cloud where the primary discrimination was the color contrast provided by the obscuration of the blue diffuse backscattered illumination by the cloud.

The flexible grid adaptivity of OMEGA permits the accurate simulation of the satellite field of view thereby reducing the beam-filling problem that can cause major discrepancies in the data retrieval algorithms. Given the interaction of the model forecast and the data retrieval, the very high resolution forecasts possible with OMEGA also could improve existing retrieval algorithms.

In this paper, we will present an overview of our concept of an analog sensor (or synthetic satellite data generation), and how the unique simulation capabilities of OMEGA factor into this concept.

1. INTRODUCTION

Current operational atmospheric simulation systems[1,2,3] are scale specific and cannot resolve the full spectrum required for the accurate forecast of the local scale phenomena that contribute to the Earth’s radiance. Even with recent advances in computational power[4], the current architecture and physics of today's generation of atmospheric models cannot simulate the scale interaction of the atmosphere sufficiently to produce accurate cloud forecasts. Recently, several groups have started the development of non-hydrostatic, nested (multiply nested in some cases) atmospheric models[5,6], however these models represent an incremental, evolutionary path in atmospheric simulation.

Table 1. OMEGA overview

Governing equations	Fully non-hydrostatic equation set
Dimensionality	3D
Grid structure	Unstructured and adaptive triangular prisms
Coordinate system	Rotating Cartesian coordinate framework
Numeric	Finite volume based upon Smolarkiewicz[7]
Surface roughness	Specified over land, predicted over water[8]
Soil surface	Based on the force-restore rate method[9]
PBL	Planetary boundary layer is treated separately as viscous sublayer[10], surface layer[11], and transition layer
Turbulence closure	*First order closure*: O'Brien K-profile for unstable conditions[12]; Blackadar local K-profile for stable conditions[13]. *1.5 order* κ-ε *closure*: Based on turbulent kinetic energy and its dissipation
Cumulus parameterization	Modified Kuo scheme[14,15]
Microphysics	Extensive bulk-water microphysics[16]
Radiation	Shortwave absorption by water vapor and longwave emissivities of water vapor and carbon dioxide and computationally efficient technique of Sasamori[17]
Initialization	Based on 4D data assimilation
Transport and diffusion	Embedded Eulerian and Lagrangian aerosol transport algorithms

The Operational Multiscale Environment model with Grid Adaptivity (OMEGA) was conceived out of a need to advance the state-of-the-art in numerical weather prediction in order to improve our capability to predict the transport and diffusion of hazardous releases. Its primary role, however, represents just a small fraction of the utility of the model. The flexible grid resolution of the model permits the study and simulation of a wide variety of scale interactive phenomena including the generation of both water/ice and aerosol clouds. Moreover, the high resolution possible using the OMEGA grid opens the possibility of using high resolution simulation to enhance the analysis of satellite data and the retrieval of physical quantities from that data.

The goal of creating a model with horizontal resolution down to 1 km and vertical resolution down to a few tens of meters determines a number of requirements imposed upon the model. It must, among other things, be fully non-hydrostatic, three dimensional, and contain extensive surface and PBL physics packages. The key feature, however, is the use of an unstructured triangular grid. The unstructured grid used in OMEGA is naturally scale spanning and adaptable. The OMEGA grid can readily adapt to fixed surface or terrain features, or dynamic features in the evolving weather. For enhanced satellite retrieval, OMEGA can provide temperature, moisture, hydrometeor, and aerosol fields which can be post-processed into spectral radiance values.

Discussions of the OMEGA architecture can be found in Bacon, *et al*[18]. A summary of the features of OMEGA is given in Table 1. In this paper, we focus upon the potential for improving satellite retrieval using model output via the creation of *synthetic* satellite data. Before we do that, however, it is necessary to have a brief discussion of the OMEGA grid structure since it is the enabling technology to accomplish the improved retrieval.

2. OMEGA GRID

OMEGA is based on an unstructured triangular prism computational mesh. This mesh is unstructured in the *horizontal* dimension and structured in the *vertical* dimension. The rationale for this mesh is the physical reality that the atmosphere is

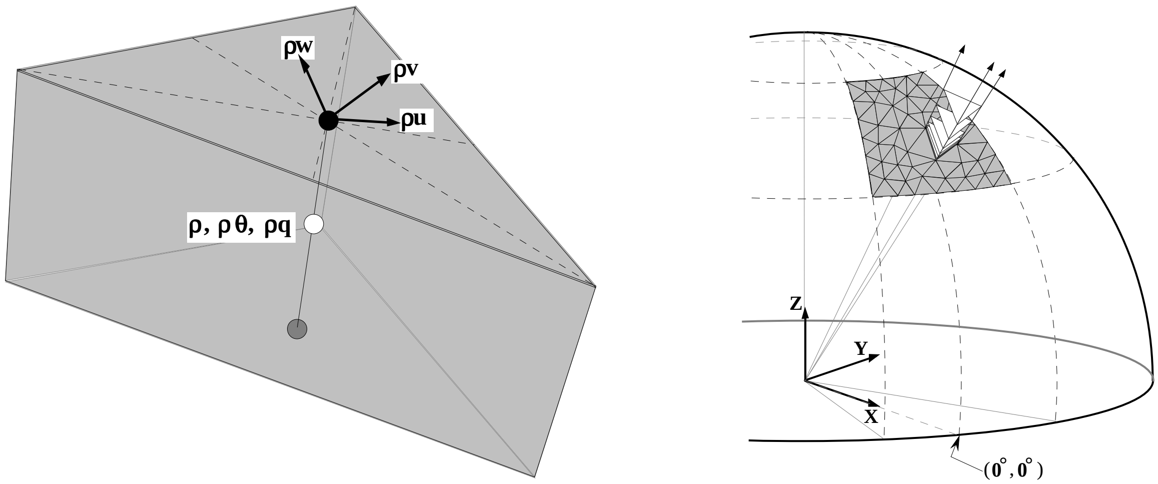

Figure 1. OMEGA grid element, coordinate system, and the vertical alignment of the OMEGA grid.

roughly decorrelated horizontally but correlated vertically. In fact, this is the reason that most **hydrostatic** forecasting systems work. While completely unstructured three-dimensional meshes have been used for other purposes[19,20], the benefit of having a structured vertical dimensional is a reduction of three orders of magnitude in the computational requirements of the model.

An OMEGA grid element is shown in Figure 1. In OMEGA, the scalar quantities are defined at the geometric center of each grid element, while the components of the velocity are defined at the center of the top face. In each case, the scalar or vector quantities represent the average of the variable over the cell, or dual cell, volume, respectively. The OMEGA grid elements are stacked vertically in such a fashion that all of the cells in a column have the same projection onto the surface of the Earth. This common projected footprint considerably simplifies the grid generation and provides an extremely simple framework for the radiation transport model. This factor makes the generation of synthetic satellite data much easier as well.

The flexibility of unstructured meshes facilitates the gridding of arbitrary surfaces and volumes in three dimensions. In particular, unstructured grid cells in the horizontal dimension can increase local resolution to better capture topography or the important physical features of atmospheric circulation flows and cloud dynamics, or to map onto a particular satellite field-of-view The underlying mathematics and numerical implementation of unstructured adaptive grid techniques have been evolving rapidly, and in many fields of application there is recognition that these methods are more efficient and accurate than the structured logical grid approach used in more traditional codes. To date, however unstructured grids and grid adaptivity have not been used in the atmospheric science community[6]. Atmospheric model problems characterized by large model domains, long time integration, and operational time constraints have not been viewed as viable candidates for the emerging computational fluid dynamic (CFD) grid technologies. OMEGA represents the first attempt to join these two communities.

The adaptation of an unstructured grid takes place through a variety of grid operations. **Vertex addition** is usually followed by a **vertex reconnection** step (Figure 2). The vertex addition step is accomplished by adding a vertex at the centroid of each affected cell and connecting it to the vertices of the cell. The reconnection step then involves the evaluation of each new cell to see if it is possible to create grid cells with a lower aspect ratio by removing an edge and reconnecting the opposite vertices.

The reverse process, **vertex deletion,** coarsens the grid and is also followed by a **vertex reconnection** step. It is important to note that even though the grid adaptation routines may create an apparent **motion** of the grid, it does not, in fact, move; rather the goal is to refine the grid in advance of any important physical process which could require additional grid resolution, and to coarsen the grid behind the region.

Vertex relaxation, in which the vertices are allowed to move as a mass-spring system, and **edge bifurcation**, which is equivalent to vertex addition in the special case of an edge cell, represent additional processes which can be used to refine the grid (Figure 2).

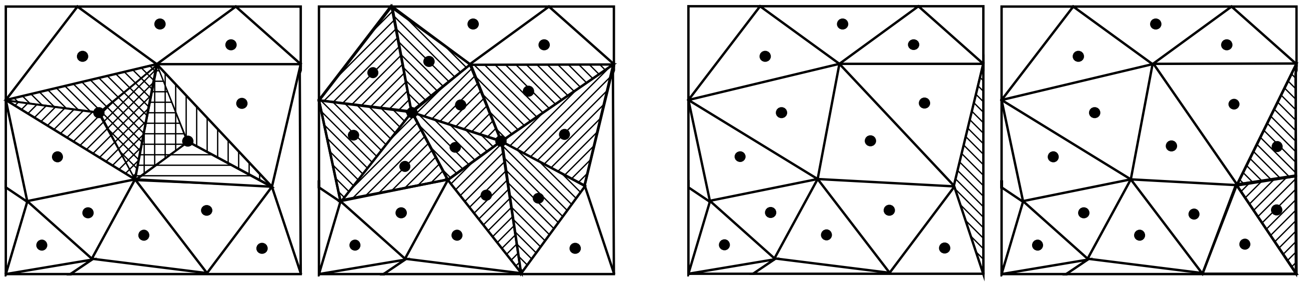

Figure 2. Vertex addition / reconnection (left) and vertex relaxation / edge bifurcation (right).

3. OMEGA PHYSICS

The major advantage of OMEGA over current state-of-the-art models includes the ability to resolve the surface terrain down to scales of 1 km by using the flexibility of the unstructured grid to place vertices only where required. In addition, OMEGA can resolve the local perturbations on the larger scale evolving weather down to the same scale. In order to accomplish this, however, it is necessary to include all of the physical parameters and processes which affect the local flows. These include not only the topography, but the land use, the land/water composition, the vegetation, the soil moisture, the snow cover (if appropriate), and the surface moisture and energy budgets. The inclusion of this additional physics, some of which is only appropriate because of the increased spatial resolution, represents an additional advance in the state-of-the-art.

OMEGA uses a fully non-hydrostatic equation set to describe the dynamics. Cloud formation, growth and precipitation processes are simulated by bulk-water parameterization schemes. A convective parameterization scheme is used in regions where the resolution is insufficient to resolve the convection explicitly. OMEGA incorporates a radiation transport package which approximates the effects of the atmosphere and clouds on the radiation budget. Finally, OMEGA contains an extensive planetary boundary layer package. The OMEGA equation set is solved using a semi-implicit scheme in the vertical and an explicit scheme in the horizontal. This balances the horizontal and vertical timestep limitations. Typical timesteps are a few seconds.

Through the incorporation of all of the surface data and the explicit and parameterized microphysics, OMEGA contains all of the information required in order to compute the reflected and emitted radiance of the Earth, including both surface and cloud reflectance, moisture and cloud absorption, and when included in the OMEGA calculation, aerosol effects. We discuss the mechanism for doing this in the next section.

4. GENERATION OF *SYNTHETIC* SATELLITE DATA

Meteorological satellites measure the radiance of the Earth in a number of bands in the visible and infrared regions of the spectrum. The current methodology for unfolding this radiance data to provide physical information involves calculation of the effective temperature from the radiance and then the assignation of this temperature to a particular level in the atmosphere. The calculation of the effective temperature involves knowledge of the radiative transfer through, at the moment, an idealized model atmosphere; the calculation of the altitude of that temperature similarly involves the underlying assumption of a model atmosphere. As a paradigm for our discussion, we chose the TIROS Operational Vertical Sounder (TOVS) instrument set. We first consider the standard weighting function analysis; we then consider the alternative possible by using high resolution model output.

4.1 TOVS Weighting Functions

The fundamental features of the High resolution Infrared Radiation Sounder (HIRS) used in TOVS can be found in Smith *et al*[21]. The first seven channels of HIRS, used for the temperature sounding, have principal contributions at 30, 60, 100, 400, 600, 800, and 900 mb, respectively. The TOVS weighting functions for these channels can also be found in Smith and are reproduced in Figure 3. In all cases, the full-width at half-maximum (FWHM) of the weighting function is over 100 mb wide. This implies that the vertical error caused by the use of an idealized atmosphere can be significant. Nevertheless, with extensive processing, the HIRS temperature retrievals can achieve roughly 1-2 degree accuracy, however, the dewpoint

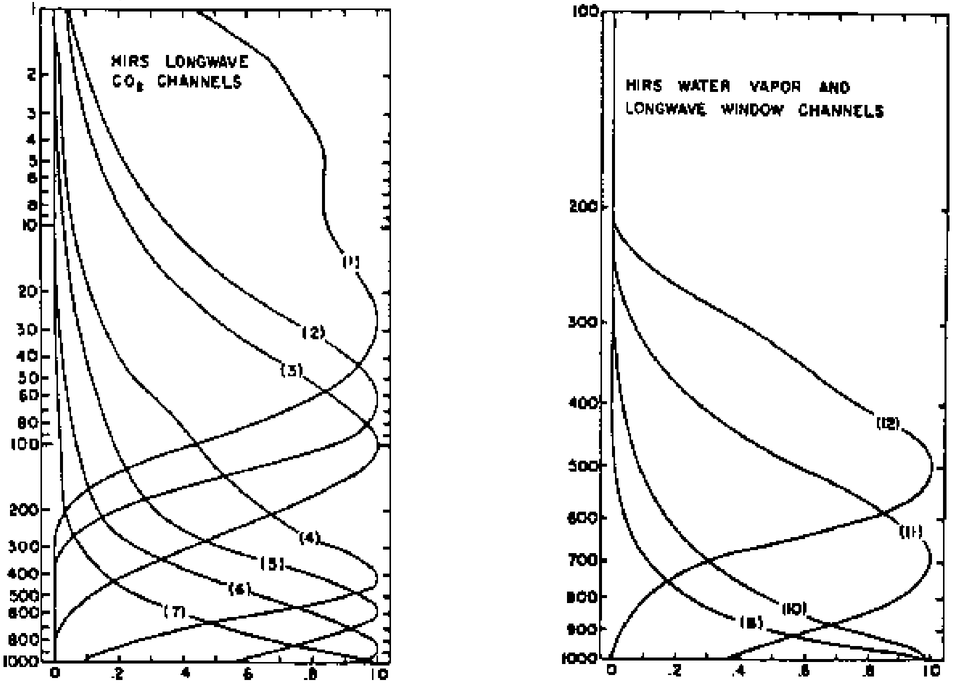

Figure 3. Normalized TOVS weighting functions. Shown are the HIRS longwave CO_2 and the water vapor channels (from Smith, *et al.*[21]).

retrievals, which are based solely upon 3 channels with FWHM between 200 and 400 mb, are off by several degrees[22]. In addition, the contamination of the field-of-view (FOV) by clouds can make the retrieval nearly impossible. The improvement of the satellite retrievals, given the amount of overlap between the different channels and the frequency of clouds, is an extremely difficult task unless other information is available. This is because the backwards deconvolution of the integral radiance equation is nearly impossible unless the basis functions are orthogonal in some norm. This is not the case with the radiance weighting functions. On the other hand, if one considers the problem from a fresh viewpoint, an alternative presents itself.

4.2 *Synthetic* Radiance Products

The forward integration of the radiance equation is far simpler than the backwards deconvolution. If one starts with high resolution model output especially if the model explicitly simulates cloud cover, it is possible to calculate the channel radiance for each of the satellite channels. This type of calculation was impossible to consider in the past due to the extremely coarse resolution (typically of the order of 100 km) of the forecast models and the lack of an explicit treatment of clouds. OMEGA, with its variable resolution and both explicit and parameterized cloud microphysics represents a new breed of model which could potentially use its variable resolution to increase the definition of air mass (temperature, moisture, cloud) definition. One can conceive of a system whereby OMEGA uses an adaptivity criterion which is based upon a particular radiance product to enable it to increase resolution in regions where large variation in radiance would otherwise make the calculation of the radiance difficult.

5. MERGING *SYNTHETIC* AND REAL SATELLITE DATA INTO IMPROVED DATA RETRIEVALS

The process of merging the synthetic and real satellite data is to first produce the synthetic radiance products for intercomparison with the real satellite data. These can then be compared with the observations to determine whether it is necessary to **nudge** the model solution. This nudging process can be accomplished with the model error statistics in mind so that unrealistic changes to the model solution do not occur. Then, starting from the top of the atmosphere, the intercomparison is carried in an iterative fashion much as a typical retrieval using the model output as the first guess in the iterative solution. The difference is that the sounding adjustments are made subject to the model error statistics and not just to the large layer information available from the observations.

In the past, the use of high spatial resolution satellite data, albeit requiring a tough inversion process, yielded important information regarding the spatial characteristics of the atmosphere, although with limited absolute accuracy. Given the resolution of models such as OMEGA, however, and the increasing complexity of their physics suite, it is possible to consider a merging of the two data sources as equal contributors to a single integrated system.

6. OTHER APPLICATIONS OF *SYNTHETIC* SATELLITE DATA

One can conceive of other uses of synthetic satellite data in addition to improvement of satellite data retrievals. These include the development of synthetic products to be used as part of a mission planning strategy, instrument development, and test and evaluation (T&E) of satellite sensor systems. Mission planning can utilize model output from a high resolution **forecast** system, such as OMEGA, to provide the planners the expected capability of various systems under the specific expected conditions. In this case, the adaptivity of OMEGA could be used to increase the spatial resolution in the region of interest. Instrument development includes building an analog of the instrument and testing it under either simulated meteorological conditions developed from either archived datasets or from idealized test situations. T&E simulation is similar to the scenario of instrument development but is more formalized in the sense of providing a pre-determined suite of acceptance tests to be applied to prototype systems as part of their final evaluation. In these latter two situations, a model such as OMEGA would be used to build consistent high resolution meteorological conditions from the relative coarse resolution world-wide data available.

7. CONCLUSIONS

OMEGA represents a new type of meteorological forecast model. For the first time, it is conceivable to consider the creation of model output products which function as digital analogs of satellite sensors. This synthetic satellite data could then be intercompared with the actual data in order to provide guidance for model **nudging** in a fashion which recognizes the importance of the satellite data but also considers it as one part of an integrated data ingest and assimilation process.

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9. REFERENCES

1. Hoke, J.E., N.A. Phillips, G.J. DiMego, J.J. Tuccillo, and J.G. Sela, 1989: The regional analysis and forecast system of the National Meteorological Center, *Wea. Forecasting*, **4**, 323-334.
2. Janjic, Z. I., 1990: The step-mountain coordinate: physical package, *Mon. Wea. Rev.*, **118**, 1429-1443
3. Mesinger, F., Z.I. Janjic, S. Nickovic, D. Gavrilov, and D.G. Deaven, 1988: The step-mountain coordinate: Model description and performance for cases of Alpine lee cyclogenesis and for a case of an Appalachian redevelopment, *Mon. Wea. Rev.*, **116**, 1494-1518.
4. McPherson, R., 1991: 2001 - An NMC Odyssey, *Ninth Conf. on Num. Wea. Prediction*, AMS, Boston, MA.
5. Dudia, J., 1993: A nonhydrostatic version of the Penn State/NCAR mesoscale model: Validation tests and simulation of an Atlantic cyclone and cold front, *Mon. Wea. Rev.*, **121**, 1493-1513.

6. Skamarock, William C., and Joseph B. Klemp, 1992: Adaptive Grid Refinement for Two-Dimensional and Three-Dimensional Nonhydrostatic Atmospheric Flow, *Mon. Wea. Rev.*, **121**, 788-804.

7. Smolarkiewicz, P. K., 1983: A simple positive definite advection scheme with small implicit diffusion. *Mon. Wea. Rev.*, **111**, 479-486.

8. Charnock, H., 1955: Wind stress on a water surface. *Quart. Jl. R. Met. Soc.*, **81**, 639-640.

9. Deardorff, J. W., 1978: Efficient prediction of ground surface temperature and moisture with inclusion of a layer of vegetation. *J. Geophys. Res.*, **83**(C4), 1889-1903.

10. Deardorff, J. W., 1974: Three-dimensional numerical study of the height and mean structure of a heated planetary boundary layer. *Boundary Layer Meteorol.*, **7**, 81-106.

11. Businger, J. A., J. C. Wyngaard, Y. Izumi, and E. F. Bradley, 1971: Flux-profile relationships in the atmospheric surface layer. *J. Atmos. Sci.*, **28**, 181-189.

12. O'Brien, J. J., 1970: A note on the vertical structure of the eddy exchange coefficient in the planetary boundary layer. *J. Atmos. Sci.*, **27**, 1213-1215.

13. Blackadar, A. K., 1979: High resolution models of the planetary boundary layer, *Advances in Environmental and Scientific Engineering*, Vol. 1, Gordon and Breach, pp. 50-85.

14. Kuo, H. L., 1965: On formation and intensification of tropical cyclones through latent heat release by cumulus convection. *J. Atmos. Sci.*, **22**, 40-63.

15. Anthes, R. A., 1977: A cumulus parameterization scheme utilizing a one-dimensional cloud model. *Mon. Wea. Rev.*, **105**, 270-286.

16. Lin, Y-L., R. D. Farley, and H. D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Clim. Appl. Meteorol.*, **22**, 1065-1092.

17. Sasamori, T., 1972: A linear harmonic analysis of atmospheric motion with radiative dissipation. *J. Meteorol. Soc. Jpn.*, **50**, 505-517.

18. Bacon, D. P., T. J. Dunn, Y-L. Ho, I. Lottati, M. D. McCorcle, S. E. Peckham, R. A. Sarma, S. Young, and J. Zack, 1993: Operational Multiscale Environment model with Grid Adaptivity (OMEGA), Proc. of the 13th Conf. on Weather Analysis and Forecasting, August 2-6, 1993, AMS, Boston, MA.

19. Baum, J.D., H. Luo, and R. Lohner, 1993: Numerical simulation of a blast inside a Boeing 747, AIAA 93-3091, 24th Fluid Dynamics Conference.

20. Luo, H., J.D. Baum, R. Lohner, and J. Cabello, 1994: Implicit schemes and boundary conditions for compressible flows on unstructured meshes, AIAA 94-0816, 32nd Aerospace Sciences Meeting and Exhibit, Reno, NV.

21. Smith, W. L., H. M. Woolf, C. M. Hayden, D. Q. Wark, L. M. McMillin, 1979: The TIROS-N Operational Vertical Sounder, *BAMS*, **60**, 1177-1187.

22. Hayden, Christopher M., William L. Smith, and Harold M. Woolf, 1981: Determination of Moisture from NOAA Polar Orbiting Satellite Sounding Radiances, *JAM*, **20**, 450-466.