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## Data/Model Integration for Vertical Mixing in the Stable Arctic Boundary Layer

Sumner Barr\*, Douglas O. ReVelle, C. Y.-Jim Kao and E. K. Bigg

### Abstract

This is the final report of a short Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). Data on atmospheric trace constituents and the vertical structure of stratus clouds from a 1996 expedition to the central Arctic reveal mechanisms of vertical mixing that have not been observed in mid-latitudes. Time series of the altitude and thickness of summer arctic stratus have been observed using an elastic backscatter lidar aboard an icebreaker. With the ship moored to the pack ice during 14 data collection "stations" and the lidar staring vertically, the time series represent advected cloud fields. The lidar data reveal a significant amount of vertical undulation in the clouds, strongly suggestive of traveling waves in the buoyantly damped atmosphere that predominates in the high Arctic. Concurrent observations of trace gases associated with the natural sulfur cycle (dimethyl sulphide, SO<sub>2</sub>, NH<sub>3</sub>, H<sub>2</sub>O<sub>2</sub>) and aerosols show evidence of vertical mixing events that coincide with a characteristic signature in the cloud field that may be called "dropout" or "lift out". A segment of a cloud deck appears to be relocated from the otherwise quasi-continuous layer to another altitude a few hundred meters lower or higher. Atmospheric models have been applied to identify the mechanisms that cause the "dropout" phenomenon and connect it dynamically to the surface layer mixing.

### Background and Research Objectives

Knowledge of the polar regions of the earth has long been recognized as crucial to the understanding of the global circulations of the atmosphere and ocean. The Arctic is particularly important because it is oceanic and two media, atmosphere and ocean, interact continuously across the entire region. Recent attention to contamination of the region by radionuclides and heavy metals from the Former Soviet Union (Crane, 1997), and prospects of expanded industrial development and fossil energy extraction, further focus scientific attention on the Arctic. The acute awareness of the extreme sensitivity of the arctic ecosystems to human impacts forces us to learn as much as we can about the systematics of this fragile yet forbidding area.

The remoteness of the Arctic has made it very difficult to acquire surface-based data on the atmosphere and the atmosphere-ocean interaction with any sense of continuity until

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very recently. An expedition on board a Swedish icebreaker in 1991 provided excellent trace chemistry and aerosol data contributing to biogenic feedbacks on cloud properties. By extension, these data revealed climatically important energy budgets from the ice edge to the center of the ice pack. Several mysteries remained regarding atmospheric properties and structure in the important three-kilometer layer above the surface. Los Alamos National Laboratory (LANL) had the opportunity to operate a lidar remote sensing system during the 1996 return expedition with the goal of providing diagnostics on clouds and the dynamical processes that influence them (convection, internal gravity waves, longitudinal roll vortices, episodic breakdowns of the stable boundary layer) (Leck, 1995).

The summertime arctic stratus clouds are scientifically fascinating because their existence and structure depend on a continuing and delicate balance of radiative (visible and IR), latent, and sensible (turbulent) heat exchange. The atmospheric models exist at Los Alamos for the quantitative computation of the radiative and turbulent transfer mechanisms that drive the processes. Kao and Smith (1996) describe the formation of multiple arctic stratus layers by a decoupling mechanism caused by absorption of solar visible radiation at the base of existing stratus. That yields a shallow thermodynamically stable layer that, in turn, suppresses turbulence and decouples the cloud base from its sea level source of moisture. This "fossil" layer persists while up to three additional layers form and decouple by the same mechanism in the lower 500 m of the atmosphere.

The lidar data set from 1996 contains over 300 hours of lidar imagery taken over a six-week period from open water at 70N to the central ice pack at 87N. It is supplemented with conventional meteorological data and trace chemical and aerosol concentrations to permit quantitative comparisons and evaluation of processes through the application of available models.

The particular research objective of this work is to focus on a signature of the time series of stratus elevations that appears to be related to mixing episodes through reasonably deep layers of the arctic boundary layer. A segment of a cloud deck appears to be relocated from the otherwise quasi-continuous layer to another altitude a few hundred meters lower or higher. We have identified more than two dozen examples of this feature in the lidar data and at least five of the cases are coincident with excursions in concentrations of trace gases or aerosols. Such a relationship is not intuitive. The stratus are located at elevations of a few hundred meters to 1.5 km above the surface while the trace constituents are measured at about 10 meters. The correlation indicates a dynamical or turbulent connection across deep layers of the arctic atmosphere. In mid-latitudes, where convection is often a dominant mixing mechanism, mixed layers of several kilometer depth are common but the very stable density profiles in the Arctic suppress convection. In that environment the

apparent coupling across the lower kilometer of the atmosphere is a surprising result that requires good dynamical models to understand. We have exercised two models and are encouraged by the preliminary results.

### **Importance to LANL's Science and Technology Base and National R&D Needs**

This work is firmly within the Laboratory's core competency in *Earth and Environmental Systems* and utilizes HIGRAD, an extremely high-resolution atmospheric model that has been developed within the *High Performance Computing* core competency. The data were collected under the Remote Sensing LDRD project and the interpretation is consistent with the goals of the *Global Environmental Systems* Tactical Goal.

The experimental data were collected as part of the international expedition, ARCTIC-96, in which a major goal was to assess the biogenic feedback from sea-borne organisms to modification of cloud optical properties. This is an important corollary of the evaluation of human-induced climate modification. The steps include:

- (1) emission of organic sulfides from the sea,
- (2) oxidation and modification of those to sulfate particles
- (3) that serve as cloud condensation nuclei
- (4) resulting in altered cloud droplet size distributions, and hence
- (5) altered scattering and absorption of visible and infrared radiation.

The mixing as diagnosed by the lidar is a crucial step in determining the quantity and location of the emissions. The other important practical problem is the transport of hazardous material across the Arctic Basin. Once again, any data and analysis that can teach us more about air-sea exchange and vertical mixing in the atmosphere will contribute significantly to an improved understanding of this important problem.

### **Scientific Approach and Accomplishments**

We have examined the data images to identify mechanisms that couple boundary-layer dynamical processes to cloud physical processes. In preliminary examination of the data it has become clear that buoyancy-driven waves in the stably stratified (thermally) boundary layer of the region play a dominant role by moving stratus cloud layers vertically over ranges of a few hundred meters. In many cases the displacement is symmetrical, cloud layers simply oscillate in the vertical and no apparent mixing takes place in the surface layers beneath the cloud. However, we have identified numerous cases where

sections of the cloud layer are detached from the main body of stratus. This is illustrated in Figure 1. These events are much more likely to be associated with turbulent mixing events that reach the surface.

Barr et al (1997) offer conceptual mechanisms in which a displaced segment of stratus undergoes additional evaporation of small droplets (in a downward displacement) or condensation (upward displacement) because of the properties of the ambient atmosphere it encounters in the original displacement. The change in latent heat alters the buoyancy of the cloud segment. It may continue to rise or fall until it finds its own new buoyancy equilibrium. The observed result of this process is an almost "cookie cutter" removal of a slab of stratus to a new altitude a few hundred meters below or above the surrounding cloud. Concurrent surface-based observations often reveal rain or snow showers, enhanced turbulence, and excursions in the concentrations of trace chemical compounds or aerosols.

We have identified a possible mechanism to explain an important phenomenon of episodic mixing in the atmospheric boundary layer of the high arctic. It remains to quantify the physical processes through the use of models that contain the appropriate thermodynamics and hydrodynamics with particular attention to cloud physics. We currently use three such models as described by Kao and Smith (1996), ReVelle (1994), and Nappo (1994)

A preliminary two-dimensional simulation was carried out using HIGRAD, a very high resolution hydrodynamic model. The calculation was initialized with the observed temperature and moisture profile for a particular case of practical interest, August 7, 1996. Figure 2 depicts an evolution of three important parameters, vertical velocity, water vapor, and cloud aerosol, at 400-second intervals over about 30 minutes. The period was well into the simulation and free of startup artifacts. A pair of vortices with dimension about 0.5 km dominate. The large vortices are strong enough to transport material across the 500m-deep mixed layer in about 10 minutes. The 20-minute lifetime of these features is sufficient to assure that a trace constituent advected into the area in the free atmosphere could be brought to the surface. The sampling of both SO<sub>2</sub> and dimethyl sulfide on August 7 show large fluctuations consistent with the circulations shown in Figure 2. Notice also that the cloud aerosol exhibits a downward protruberance. The cloud feature and the trace constituent mixing are consequences of the same circulation pattern, the organized roll vortices that fill the layer between the surface and the inversion at 500-m altitude.

A detailed first draft of a paper was written for submission to the *J. Geophysical Research* in January 1998 with the title: "Bursting in the High Arctic, Atmospheric Boundary Layer: Results from the International Arctic Ocean Expedition 1996-AOE-96," by D.O. ReVelle, E.D. Nilsson and M. Kulmala. This work is a continuation of work

begun over two years ago when E.D. Nilsson and D.O. ReVelle rewrote a one-dimensional computer code, originally developed and fully tested by ReVelle, which added new physics and chemistry to produce a code, BLMARC, that could efficiently and relatively quickly handle all of the new data that would result from the three-month Arctic Ocean Expedition to the North Pole during the summer of 1996. It was during this expedition that the Los Alamos lidar was used to record data on aerosol backscattering in the High Arctic. A very brief summary of the key features of BLMARC includes:

- 1) a first-order turbulence closure model (constrained by second-order closure tests),
- 2) a parameterized but realistic long-wave radiation model,
- 3) a relatively simple air-flow chemistry model (with 67 chemical substances included),
- 4) an atmospheric aerosol model with feedbacks to clouds, radiation and to air flow chemistry,
- 5) a simple stratus cloud model,
- 6) a force-restore model for the detailed energy exchanges at the lower boundary of the model (This was originally developed for soil at middle latitudes and modified for high latitudes over ice/snow surfaces. The energy exchange is linked both dynamically and energetically to the surface layer behavior.),
- 7) a surface-layer, Monin-Obukhov, similarity -theory approach below about 10 meters,
- 8) a "Ekman-layer" eddy regime aloft that is linked at its interface to the surface-layer behavior,
- 9) utilizes the moisture availability parameter to specify the water loading of the lower boundary, and
- 10) uses inputs of wind speed, direction, potential temperature, water-vapor mixing ratio, etc. for initialization and forecasts the future state of the boundary layer using a variable time step (satisfying the linearized CFL stability criterion as a function of the degree of turbulence predicted).

It is on the detailed physics involved in item (7) that the current paper is focused. A similar paper is also being written by E.D. Nilsson on the ability of the model to properly predict the dynamical 12-hour repeatability of the low-level jet in the High Arctic atmospheric boundary layer. Briefly, bursting is defined as a relatively rapid variation in the air temperature and mean wind speed, etc., during periods in which relatively smooth behavior is first expected. It is intimately connected with the near balance between the turbulent flux divergence and the radiative flux divergence in the energy conservation equation for the surface layer potential temperature. It also directly involves the dynamical flow transition between laminar and turbulent flow in the surface layer. During periods



when the radiative flux divergence is most important in providing cooling, the layers involved are predicted to be in a state of laminar flow. Conversely when the turbulent flux divergence dominates the flow, the heated layers are predicted to be in a state of turbulent flow. This transition happens as a function of the specified bulk-layer Richardson number,  $Ri$ , that is continuously computed throughout the numerical integration. Because of the rapid variations predicted, it is not very sensitive to the precise critical value and can even successfully incorporate a hysteresis effect with two widely separated critical values, i.e.,  $Ri = 0.25$  and  $1.0$ . The time scale between bursting events is a strong function of the inverse of the Coriolis parameter and of geostrophic wind-speed changes as shown by ReVelle (1993) for middle latitude bursting events.

### Publications

1. Barr, S., Bigg, E. K., et al., 1997, "Lidar Investigation of Atmospheric Mixing and Its Near Surface Effects Over the Central Arctic Ocean in Summer," to be submitted to *Tellus*.
2. ReVelle, D.O., Nilsson, E.D. and Kulmala, M., "Bursting in the High Arctic, Atmospheric Boundary Layer: Results from the International Arctic Ocean Expedition 1996-AOE-96," manuscript prepared for submission to *J. Geophysical Research*.

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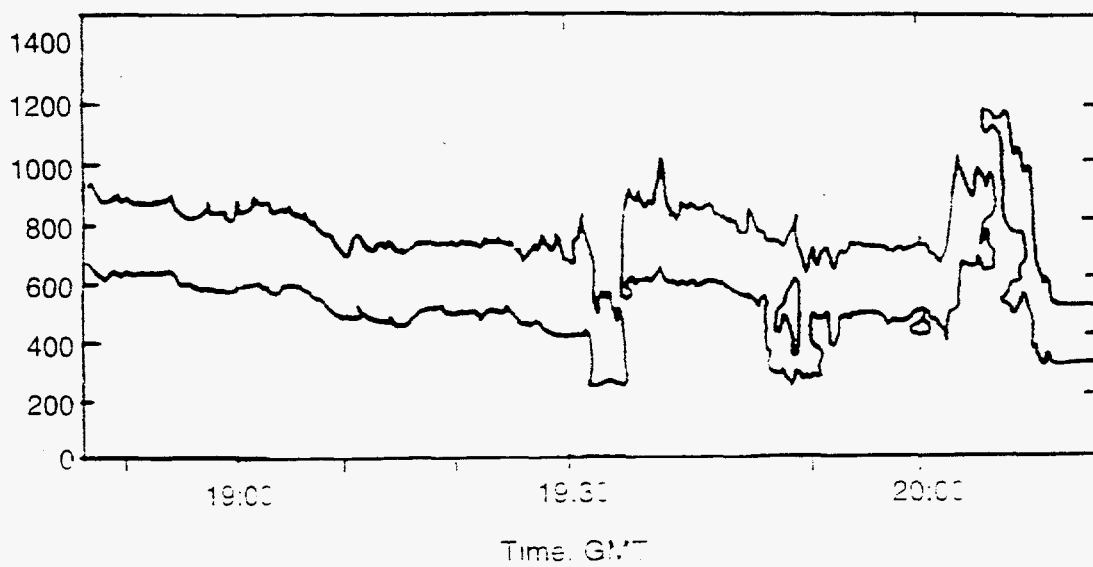


Figure 1. A copy of lidar imagery that displays stratus "drop outs" at 1935 and 1950 GMT and a "lift out" event at 2005-2012 GMT.

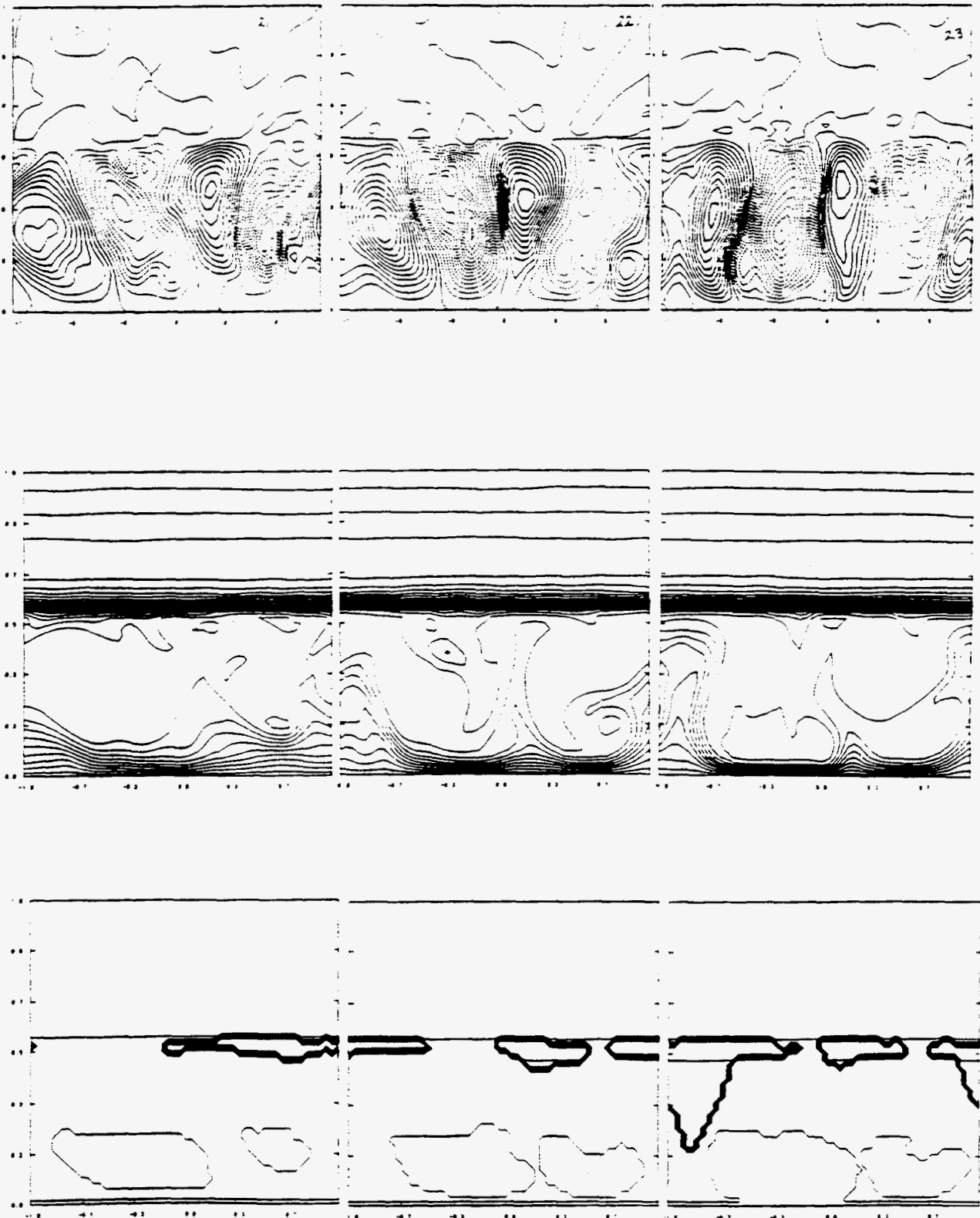


Figure 2. Evolution of three parameters—vertical velocity (top), water vapor (middle), and cloud aerosol (bottom)—at 400-second intervals over about 30 minutes, taken from HIGRAD model output.