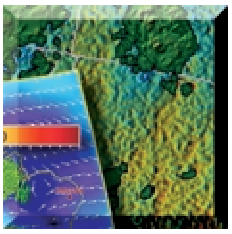

Serendipity in the Use of Satellite Scatterometer, SAR, and Other Sensor Data

Robert A. Brown

When marine geophysical measurements reach resolutions of ten to hundreds of meters over 1000-km regions, a new realm of analysis is opened. Such data did not exist prior to Seasat in 1978. However, the value of these data has been neglected for almost two decades. The reasons are many: Star Wars, modeler indifference, fear of a new form of data where empiricism reigns, and numerical model mysticism. Now the Seasat microwave sensors, finally including synthetic aperture radar (SAR), are coming of age. Organized large eddies (OLEs) that are endemic to the geophysical planetary boundary-layer (PBL) solution exemplify the new phenomena that are revealed in SAR data. Theory for OLEs has existed for 30 years. If they are truly as common as SAR data suggest, then Geophysical Climate Model PBLs must be improved, buoy data corrected, and climatology revised. (Keywords: Boundary layer, Climatology, PBL, Remote sensing, SAR.)

INTRODUCTION

Theoretical planetary boundary-layer (PBL) work has turned out to have a marvelous synergy with microwave marine remote sensing. The PBL is crucial to using the basic product of marine surface small-scale roughness, and hence momentum flux or surface stress. This is the boundary condition for flow in the atmosphere and the ocean. But the synergy is definitely a two-way street, as lately the satellite data have been verifying PBL theory. In this article the evolution of products from the satellite scatterometer is presented, and an example of the extraction of PBL-scale organized large eddies (OLEs) from synthetic aperture radar (SAR) data is given.

The procedure for selecting satellite sensors to fly is imprecise. They are expensive instruments, and command judgments must sometimes be applied to choose which is most valuable. This is not an enviable job, since mistakes can set back science for a decade. When the program is a satellite SAR involving considerable expense, it is natural for agencies to be cautious about funding decisions. All they can do is ask the scientific community about its value. And there is a scientist on every side of every polygon. This is OK; the diversity is grist for science. But the process of evaluating each scientific conjecture can be long. In the case of justification for SAR satellites, it was 17 years between Seasat and Radarsat.

Justification requires showing that the instrument has a good prospect of producing a valuable parameter. This requires two steps: (1) showing that the parameter can be obtained, and then (2) showing that the parameter is valuable to science. This article is concerned with the latter. In addition, I will show that there is another important aspect in flying new sensors; that is, a considerable life exists beyond and independent of the initial sales process for the sensor. When a satellite sensor is flying and producing data, the result is often a plethora of unexpected and serendipitous uses.

Data from satellite sensors have important applications in weather and climate analyses. These features are simply states—short- and long-term—of the basic fluids, the atmosphere, and the ocean. They are described remarkably well by the Navier–Stokes equations for fluid flow, with the addition of a rotating frame of reference. The dependent variables are pressure and velocity (momentum and continuity equations). When the energy and state equations are added, temperature and density are included variables. These parameters are well known but seem to get lost in the debate over their importance.

A SAR produces unique data. That this is one of the rare, true uses of the word unique is seen in a quick summary of the competition (Table 1). SAR radar images yield pictures and data on a global scale at unprecedented resolution. It is safe to say that the uses of these data have barely begun to be tapped. Efforts are under way to use the high-resolution information in the arcane fluid mechanics of boundary-layer theory that reveals new aspects of the turbulent flux processes (see the article by Young, this issue). These could produce conclusions that revolutionize the understanding of air–sea fluxes and overall energy balances. All that is known for certain is that the SAR is yielding new information in an area that could have important ramifications to weather and climate analyses. As a suggestion of what might result, it is instructive to examine what has evolved with another satellite radar and how it predicts that we can expect much more from a successful new data set than anyone could anticipate. As an example, we show an analysis of SAR data demonstrating that OLEs are general PBL occurrences.

In the case of a satellite SAR, Seasat-SAR has demonstrated that several geophysical parameters can be obtained from the normalized backscatter cross section, σ_0. The unexpected resolution of ships, including submarines and submarine topography, were added incentives to flying a SAR. From a geophysical standpoint, this article emphasizes the value of sensor data plus their collateral serendipitous products.

HISTORY

In 1978, the National Aeronautics and Space Administration (NASA) launched the Seasat satellite. It carried a suite of five instruments devoted to ocean

Table 1. Limitations of surface wind measurement techniques.

Data source	Limitations
Ships	
Ships of opportunity	Ship blockage effects; variable mast heights; sporadic coverage
Oceanography ships	Same as above, but only very specific coverage
Meteorology ships	Same as above, but winds are calibrated versus buoys; being phased out to buoys
Buoys	
Monster buoys (10 m)	Tilt problems in high winds and sea state; displacement height; few exist
Regular buoys (2 to 6 m)	Same as above, but tilt is worse; 8-min average; limited coverage
General Circulation Models	
Weather and climate	Resolution limits; poor PBL approximations; limited initialization data
Large eddy simulation	Needs 50 layers for 100-m resolution; hence 5 × 5 × 2 km limited domain
Direct numerical simulation	Lateral boundary conditions imposed; limited Reynolds number capability
Analytical	Parameterizations required; equations invalid at equator
Satellite sensors	
Microwave	Measures surface roughness; needs boundary-layer theory, parameterization
Radiometers	Wind speed now, direction possible; water attenuation; needs buoy calibration
Scatterometers	Wind vector calibration from buoy or General Circulation Model
SAR or altimeter	Wind model function from buoys; greatly increased resolution
Lidar	Direct Doppler measurement; mean PBL wind; limited sampling

research and lasted 99 days until a massive power failure occurred. Widespread data analyses took 10 years and continue today in some quarters. Seasat was an oceanography project. The active microwave radar scatterometer on Seasat was meant to determine the surface stress for ocean models, and the active radar altimeter was to register sea surface heights to provide the ocean geostrophic flow. The passive Seasat radiometer was designed to measure water vapor and liquid water between the satellite and surface, primarily as a correction for the attenuation of surface stress data. Finally, the active SAR was to determine the sea state and wind speed at superior resolution. There was also a visible and infrared sensor designed to determine sea surface temperatures, but it performed only moderately well. The microwave instruments were all successful for their design purposes, and oceanographers have been clamoring for follow-up sensors to be launched with mixed success. The serendipitous use of these Seasat data for atmospheric records and research was successful to a degree that has only become evident to the meteorology community decades later (Table 2).

SAR PRODUCTS AND VALIDATED DATA

A few SARs have flown in space, and several more are coming. The initial premise of microwave sensing—that a correlation exists between a backscatter signal produced by the capillaries and short gravity waves (1 to 6 cm) and the surface stress (and thereby the surface wind speed)—has been thoroughly validated during the past 20 years. From the SAR data, the spectral distribution was used early to identify atmospheric PBL-scale variations of the short waves on the surface.[1,2] Many others have reflected qualitatively on the myriad oceanic and atmospheric low-frequency waves that appear in SAR images (Figs. 1 and 2). An incomplete summary of SAR atmospheric products shows many have been discovered beyond the original goal, as indicated in Table 2. In addition to these, additional products have been derived in synergy with other sensors.

Discovery of Surface Effects of OLEs or Rolls

Although the nonlinear theory and model for OLEs in the PBL has existed since 1970, the only validating data were indirect parameters or specifically targeted areas in which OLEs were expected (e.g., convective regimes such as cold-air outbreaks). Indeed, the lack of low-frequency signal in the abundant surface-layer data led to the construction of the similarity PBL model, with OLEs only in the Ekman portion of the two-layer model (Fig. 3). As this model was used in scatterometer verification studies, it became evident that the different physics in a nonlinear PBL containing OLEs led to winds and fluxes that differed from those found with conventional K-theory representations of turbulence. This includes the approximate higher-order closure numerical models used in General Circulation Models (GCMs). The issue of prevalence of OLEs becomes

Table 2. Atmospheric products.

	Product		
Source	Designated	Possible (expected)	Unanticipated
Seasat (less SAR)	Integrated water vapor Cloud liquid water Waveheights Surface stress vector	Rain rates Sea surface temperature Storm details	Front location Sea ice displacement Sea ice concentration Latent heat flux Monthly mean humidity Surface pressures PBL stratification, thermal wind Mean PBL temperature
SAR	Wind speed Pack ice boundary Sea state	Surface stress Sea ice concentration Front location Storm location Land vegetation Swell	Wind vector Sea ice displacement Surface pressure fields Roll signatures Marine topography Rolls PBL turbulence, height, stratification

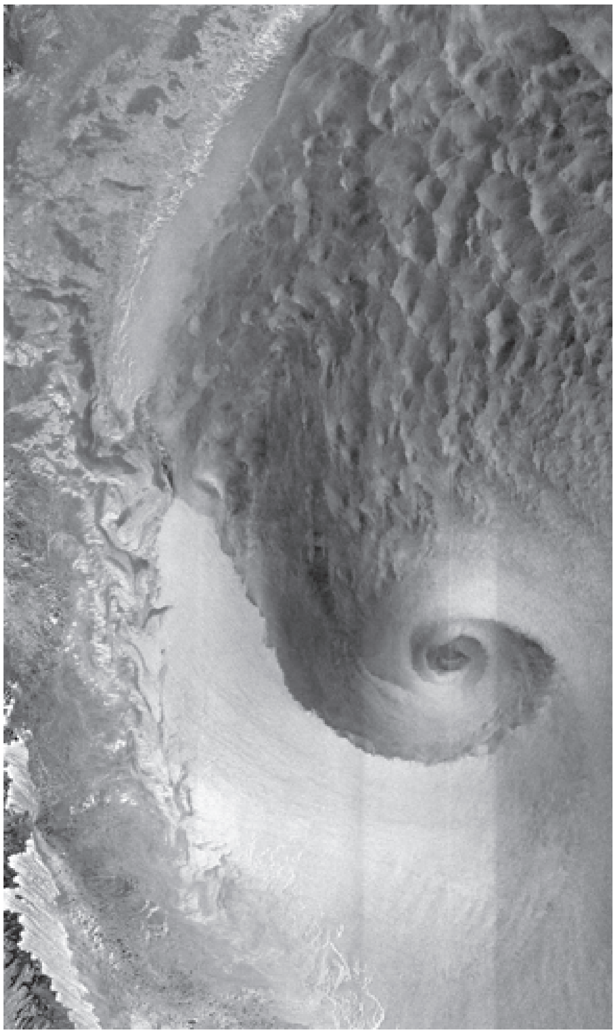

Figure 1. A 400-km-wide Radarsat image of 30 January 1997 at 2130 UTC in the Labrador Sea. One can see the low center, the sharp shift in wind direction and speed at the front, very low frequency eddies/waves in the north, and other ice, ocean, and atmospheric signals. (© Canadian Space Agency.)

important since this eddy scale cannot be physically represented in a GCM PBL model, suggesting that important physics may be missing. Despite the theory, the lack of observational verification of OLEs resulted in the lack of incentive to correct the models.

Surprisingly, SAR revealed that a sufficient impact of OLEs reached the surface to reveal itself in the changed density of the microwave-scale waves. Clearly, an enhancement/suppression of these waves occurred along the OLE convergence/divergence axes. The downdraft regions of the OLEs brought higher-momentum winds to the surface. This orientation of the OLEs was used[4] to assign wind directions to the Seasat SAR wind speeds in a first demonstration of synergy between scatterometer and SAR. OLE imprints in the SAR spectra have since been shown to be ubiquitous.[5–7] We have found[8] that a statistical subsample of SAR images over available ocean data showed OLEs occurring over half the time, as evidenced by the following statistics.

Number of images (51 km^2): 2300
Number after filter: 1882
Percent with rolls: 44
Percent without rolls: 34
Percent uncertain: 22

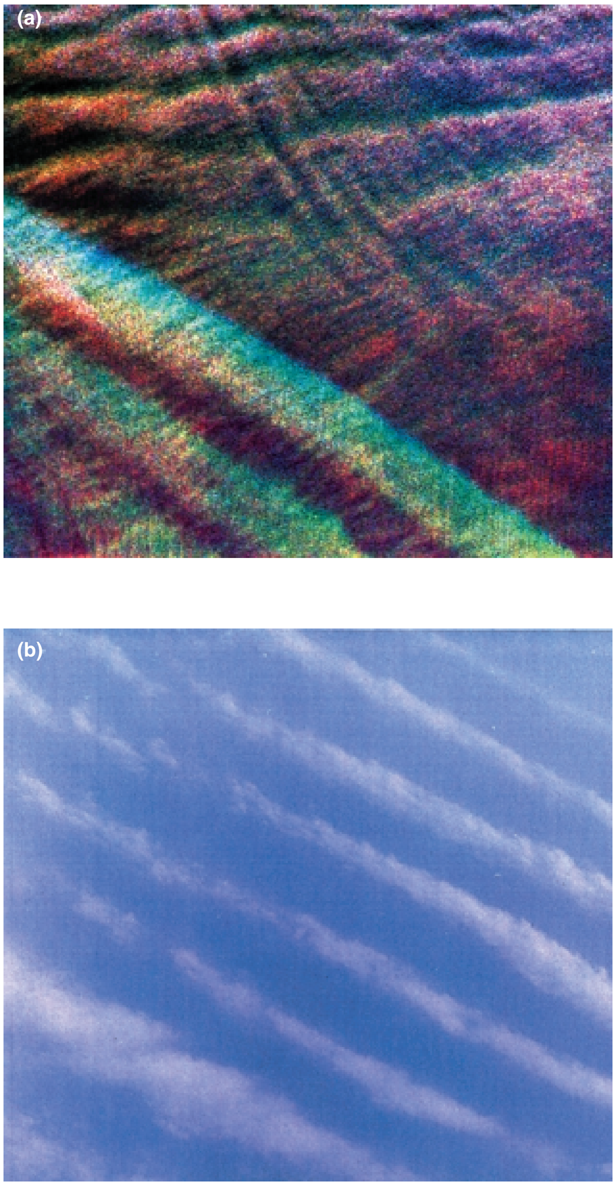

Figure 2. Images of a region of the New York Bight, 15 July 1992. (a) Jet Propulsion Laboratory aircraft SAR (AIRSAR) multispectral image[3] shows low-frequency ocean waves (top) and rows of enhanced/suppressed backscatter at about a 1-km wavelength (lower left). (b) A simultaneous visible photograph of the same region shows cloud streets, also with wavelengths of about 1 km, with the same orientation. The cloud streets and the SAR "rows" emanate from the same atmosphere dynamics, related to the OLE in the PBL flow.

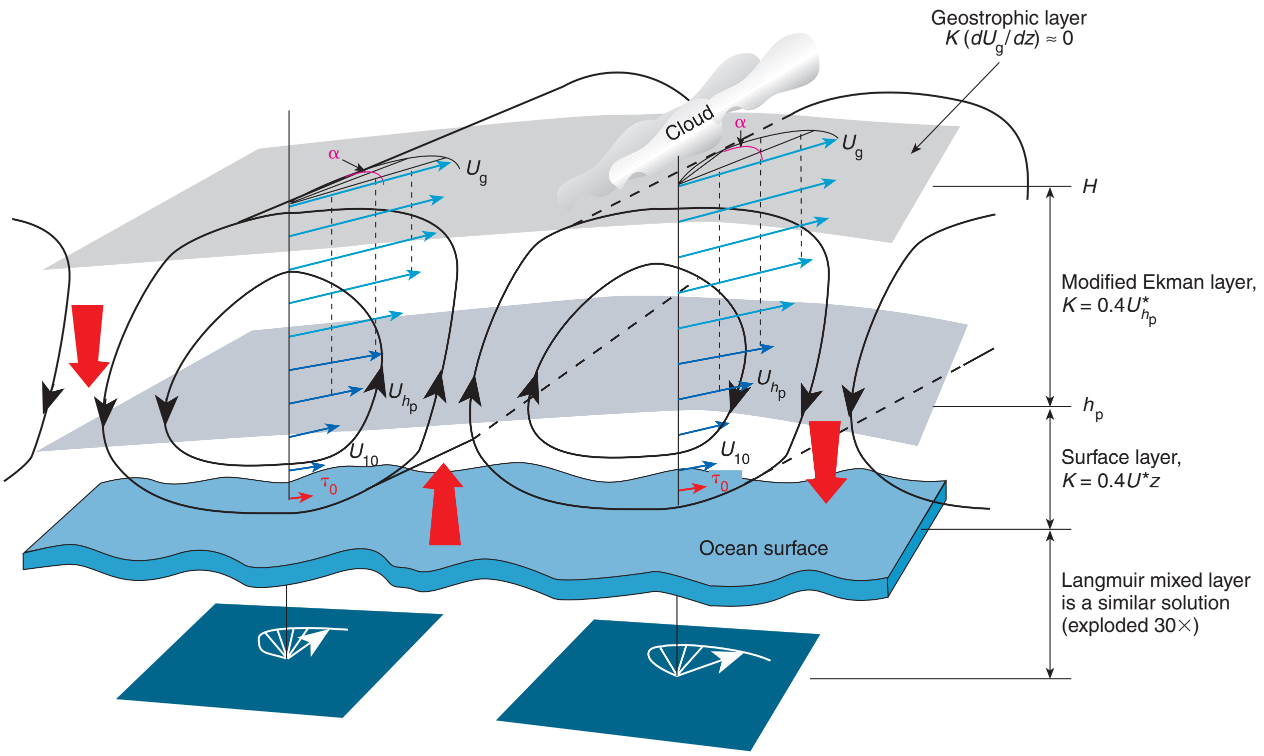

Figure 3. Sketch of two-layer similarity model for the PBL. Shown are boundary layers (modified Ekman layer, dark blue; surface layer, light blue, OLEs (circular patterns), geostrophic wind (U_g), patch height (h_p), 10-m wind (U_{10}), angle of turning (α), and surface stress (τ_0). (K = eddy viscosity, H = height of the geostropic layer, and U^* = surface friction velocity.) Large red vectors indicate direction of fluxes (momentum, heat, moisture, etc.).

The 44% occurrence of rolls is a lower limit, as often the perturbation would not be sufficient to register in the SAR signal. An observational proof of OLEs as a general PBL solution has some far-reaching consequences. The increased mixing from the strong advective vertical transport of the large eddies increases momentum flux (surface stress), a driving force for ocean mixed-layer models. It also will increase overall heat fluxes. These variables may have to be increased in climate models and the climatological record.

One significant contribution of Seasat and subsequent global satellite data has been to reveal the often sorry state of global data records and analyses. It is important to realize that the Seasat data arrived in a data vacuum comparable to the sensor's environment. Climate records were and are often grand examples of creative extrapolation. As public concern over global warming and extreme weather events has arisen, the science community has been fettered with data that have a noise level dangerously close to the significant level of parameter variation. Little chance is seen of improving the quality and quantity of *in situ* data to an adequate level. The only hope is in improved satellite global data.

Obstacles are present to the acceptance of this new regime of satellite data by establishments that have done generally admirable work in filling in the holes where data were absent. The great success of numerical models in extending forecast and climate projections has created a broad confidence in these products. For instance, when about 20 Earth Observing System science investigators were asked whether they needed scatterometer data to improve their flux parameterizations, they generally replied that they expected the numerical models to furnish this information in a more compatible, evenly distributed, global grid, *and* in color. It is now evident that this expectation is unrealistic.

Consequently, any improvements in the global marine climatological data set can be extremely valuable. Based on experience with another (much lower-resolution) imaging radar, the scatterometer, one can expect further breakthroughs in geophysical data inferences when the higher resolution of the SAR is widely available.

Serendipity in Scatterometer Data

The Seasat-A Scatterometer System (SASS) was designed to determine the driving force behind the oceanic mixed layer, i.e., the surface stress vector. Since marine stress measurements were unavailable to establish correlation models, the surface wind model function was established, from which surface stress could be extracted. In addition to oceanographic stress field use,[9] wind fields had many meteorological applications.[10] Despite this great promise, NASA was unable to put another scatterometer in space, as funds were redirected. This postponed progress until a NASA scatterometer was finally launched on a Japanese satellite in 1996. The altimeter suffered a similar delay. Only the radiometer was made operational by the Defense Meteorological Satellite Program as the Special Sensor Microwave/Imager series with remarkable success. Fortunately, the European Space Agency put up a limited SAR/scatterometer combination, European Remote Sensing Satellites 1 and 2, in 1991 and 1994, respectively. Data from these efforts demonstrated the high value of both instruments.

The geophysical data products that can be derived from scatterometer data continue to expand. A sequence of papers has been produced on the scatterometer as an anemometer,[11] a barometer,[12] and a thermometer.[13] The fact that σ_0 correlates with mean values of surface wind and surface geostrophic wind (pressure gradients) allows basic information on the stratification and baroclinity of the PBL to be inferred. Basic synoptic-scale PBL research is facilitated.

In the pursuit of a wind model function for the scatterometer's backscatter cross section σ_0, several observations became apparent: (1) The number, scale, and accuracy of ocean buoy data were insufficient. Model functions established with these data did not show winds above 23 m/s in over 70,000 comparisons and exhibited serious wind speed and directional problems in light winds. (2) The number and scale of GCM surface wind products agreed well with global scatterometer data. They have been used in establishing a model function. Although accuracy could not be determined, there was evidence that these estimates were likely to be deficient at low winds (too high in magnitude and with poor directions) and also at moderate to high winds (too low).[14,15] (3) The advent of surface pressure as "surface truth" suggested that the scatterometer wind model function produced winds that were too high at low wind speeds and too low at high wind speeds (about 10% for $U > 10$ m/s).[16] This implies that climatological turbulent heat fluxes are 10% too low, and surface stresses are 20% too low. The new NASA scatterometer model function has been adjusted to account for this. (4) The University of Washington similarity PBL model that contains the momentum flux enhancement of the OLEs predicts that storm winds can be in the 40-m/s range for significant regions of storms. This possibility must be resolved. (No collaborating data are available aside from some old weather-station ship records.) It would have far-reaching consequences to oceanic mixed-layer modeling and climatology (e.g., there will be huge turbulent heat fluxes in these regions, and the stress driving the oceanic layer will be greatly enhanced). It is evident that there is large feedback between the satellite data verification process and investigations of the quality of surface measurements.

CONCLUSIONS

Satellite data have introduced a new era into global weather and climate analyses. These data are often incompatible with conventional methods of analysis. They offer the opportunity to discover new phenomena and improve climate prediction. These conclusions are based on one aspect of scatterometer σ_0 inferences and one example of an unexpected SAR product. The surveillance, sea-state/wave spectra, and marine topology analyses and applications will surely produce other serendipitous results from SAR data.

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