This presentation will describe the practice of, and prospects for, using surface vector winds (SVW) from spaceborne platforms to drive global and regional ocean models. Interest in efforts of these kinds is motivated by the recognition a) that the surface wind vector is an essential component of the momentum flux between atmosphere and ocean, and b) that the surface wind speed modulates the fluxes of heat (sensible and latent) and material properties (i.e. gas exchanges) across the air-sea interface. The interface of abundant and precise SVW information with sophisticated numerical models for the ocean circulation is a non-trivial exercise, and several approaches to the problem have emerged within the community. SVW data from space-borne observing systems occur on time and space scales that are as much determined by practical considerations of orbit, signal processing, and data rates as they are by the natural scales inherent in the surface wind process over the ocean. Similarly numerical ocean models are constrained by practical considerations such as available computing power, sub-grid scale parameterizations, etc. By simultaneously exploiting the unique and valuable properties of data and model, and by sensibly ameliorating their respective deficiencies, optimal results can be obtained.

1 Properties of SVW Observations from Satellites

Unique properties of SVW data from spaceborne platforms both facilitate and complicate applications to ocean numerical models. Chief among the properties of interest are unprecedented spatial resolution, disproportionate temporal resolution with respect to synoptic scales of the ocean surface wind process, and SVW retrieval challenges in raining conditions. These properties are reviewed here with an eye toward applications to ocean numerical modelling.

1.1 high-wavenumber content

The within-swath resolution of SVW observations from space has been revolutionary from the early days of the ERS-1 mission in 1991, through the present-day QuikSCAT (QSCAT) mission. These data have revealed details of synoptic scale organization (e.g. fronts, cyclones, etc.) in the surface wind field that are not resolvable by any other observing system. One surprising result was the persistence of high-resolution features in long term average global wind stress curl and wind stress divergence fields (see Chelton et al. 2004).
High resolution effects can be summarized in a different way in the calculation of kinetic energy (KE) vs. (spatial) wavenumber (k) spectra as depicted in Figure 1 for a domain that spans large regions of the Mediterranean Sea over 4 years of the QSCAT mission. These are compared with KE from surface vector winds derived from numerical weather prediction (NWP) models (i.e. at ECMWF and NCEP) for the same period and regions of the Mediterranean. What is, by now, a well-known discrepancy in the high-wavenumber KE amplitudes at higher wavenumbers is evident in the figure. The spectra from scatterometer data exhibit a nearly constant slope from spatial scales on the order of $600 \text{ km}$ to the Nyquist wavenumber of $50 \text{ km}$. We refer to an approximate power law spectral property. In contrast, the spectra from weather-center winds depart from constant slope behavior at spatial scales many times larger than the NWP model resolutions. Implications of this discrepancy in the local KE budget and its impact on ocean mesoscale simulations will be discussed.

The approximate power-law property of SVW from satellites is a global characteristic of the SVW, with regional and seasonal variations that are quantifiable. Figure 2 depicts the distribution of annual-average spectral slopes in KE vs. k spectra for 2000 as computed in $8^\circ$ bins that tile globe from $70^\circ S$ to $70^\circ N$. To avoid spectral artifacts, these slopes are based on wavelet coefficient amplitudes for $8^\circ$, $4^\circ$, $2^\circ$, and $1^\circ$ wavelets in each box. The spectral slopes derived in this way have been shown to be equivalent to Fourier spectral slopes while avoiding issues of stationarity, periodicity, tapering, etc.

Figure 2 demonstrates that spectral slopes are shallower (i.e. $\sim 1.7$) in low-latitude regions of persistent tropical convection, and steeper (i.e. $\sim 2.0$) in mid-latitude regions where the dominant source of synoptic variability in surface winds is associated with baroclinic processes (waves, instabilities, etc.). This pattern, and its annual march (see righthand panel Fig. 2) is repeatable from year to year through 2004. It is a global property of the SVW that should be preserved in deriving a global ocean model forcing dataset.

1.2 temporal sampling

All recent scatterometer systems flown in space have been aboard platforms in low-earth orbit (ca. 800 km altitude), in polar-orbit orientations. These orbit configurations maximize global coverage, with gaps, in the shortest time span. They do not lead to closed-form expressions for sampling frequencies at a given point on the Earth surface. Schlax et al (2001) published the definitive analyses of the sampling characteristics of polar-orbiting, swath-based scatterometer systems from ERS-1 through QSCAT, including considerations of a so-called tandem mission. Their work demonstrates that a single, broad-swath, high-resolution scatterometer system (i.e. of the SeaWinds class) is not sufficient to resolve synoptic scale temporal variability everywhere on the globe. In other words, the temporal and spatial sampling of single scatterometer systems in space are disproportionate. Within-swath resolution is sufficient to resolve synoptic scales in the surface wind field, but the irregular and infrequent repeat timescales (ca 11–12 hr) are not. Issues for ocean model applications of SVW associated with space-time disproportionality in synoptic scale representations will be explored.

1.3 all-weather SVW retrievals

SVW retrievals are contaminated by rain in active scatterometer systems, and by atmospheric water vapor, liquid water, and/or clouds in passive polarimetric systems (i.e. WindSat). For the scatterometer systems, light rain leads to biases in the retrievals toward higher than validated wind speeds, and heavy rain toward lower wind speed biases. Wind direction orientations are often directly across-track when contaminated by rain. Sophisticated rain-flag algorithms have been developed to preclude SVW retrievals in a wide-range of raining conditions. But recent work demonstrates that these rainflags are probably too conservative, and that space-time coherence of synoptic structures in the SVW field can be improved when rainflags are ignored for wind speeds greater than 15 $\text{m s}^{-1}$ (Milliff et al., 2004; Freilich and Vanhoff, 2005).
2 Global and Regional Ocean Model Requirements

The properties of SVW data from space (reviewed above) interface with properties and requirements of regional and global ocean numerical models that can be specific to each application. Ocean models that include realistic coastlines and bathymetry are typically discretized into fixed grids with prescribed spatial resolutions. Difference approximations to the fluid equations are derived for numerical solution in the discretized space. Stability and conservation laws dictate maximum timestep size in temporal discretizations with respect to each spatial discretization. That is, the temporal and spatial discretizations are required to be proportional. Finally, sub-grid scale phenomena that occur at resolutions finer than the grid resolution can affect the resolved scales and therefore must be parameterized. These properties and requirements of ocean numerical models dictate manipulations of SVW to be used as forcing for ocean model applications.

2.1 Ocean Model Grids

The SVW retrievals from satellite observations must be interpolated from the native swath-based format to the specific ocean model grid for each application (regional, global, seasonal, forecasts, etc.). These interpolations are non-trivial if the advantages of SVW data over NWP winds are to be communicated to the ocean model (i.e. high precision, high-wavenumber KE).

Interpolated SVW datasets are produced and distributed by a handful of centers around the world. These include: datasets from IFREMER/CERSAT; Florida State University/COAPS; NASA/Jet Propulsion Laboratory; J-OFURO datasets from Tokai University, Japan; and a blended QSCAT-NCEP Reanalysis dataset produced by us at Colorado Research Associates (CoRA), and distributed through NCAR.

The interpolation methods differ for each of the widely available gridded SVW datasets, and the details of these differences are beyond the scope of our discussion here. The important point is that the interpolations should be judged in light of the specific ocean model application, and considered in terms of how well the unique properties of the SVW data are preserved. For example, the FSU/COAPS interpolation is based on a vorticity-conserving constraint, the IFREMET/CERSAT interpolation is a carefully tuned Kriging procedure, and the CoRA blended product derives from a constraint to preserve and mimic regional KE(k) properties of the SVW data.

It should also be noted that both ECMWF and NCEP assimilate some or all of the available SVW data from spaceborne platforms, and report their surface winds in gridded format. For example, ECMWF has included QSCAT data in its assimilations since 2000. However, recalling Fig. 1, it is clear that essential KE(k) spectral properties of the SVW data are not being preserved in the assimilation.

Historically, the spatial resolution of SVW data from space has been much finer than global ocean model resolutions, and of the same order as regional ocean model grids. With increasing computing power, these relations are changing. Standard OGCM resolutions (i.e. near the equator) are now commonly $1^\circ$ or finer, and regional ocean model resolutions can be significantly finer than the highest resolution SVW data (i.e. $\frac{1}{16}^\circ$). Another emerging requirement for regional ocean models involves near-coastal (and near ice-edge) winds at high resolutions. Conservative coastal and ice-edge masks in the standard SVW datasets are being re-worked now in response to this need.

2.2 Proportional Synoptic Spatio-Temporal Resolution

Temporal and spatial resolutions are required to be proportional to maintain numerical stability in ocean models. But the proportionality occurs at time and space scales much finer than the synoptic variability of the surface wind process. For example, ocean model timesteps are on the order of minutes, while synoptic systems evolve on timescales of a few hours. SVW data from a single spaceborne platform do not contain temporal scales
finer than about 12 hr resolution, so if synoptic timescales are to be included in gridded SVW products, they must be derived from another source. Typically, twice-daily or four-times daily fields from gridded wind products are interpolated to the ocean model timesteps.

This is in contrast to synoptic spatial scales which are well resolved within the SVW data swath. For this reason, the space-time interpolation problem to optimally organize SVW data on ocean model grids is largely treated as a spatial interpolation problem, with averaging or blending methods used to represent temporal variability. True synoptic temporal variability is difficult to achieve in these methods.

A pressing need in terms of augmentation of the SVW observing system from the ocean model application perspective is the maintenance of at least 2, coordinated, broad-swath, high-resolution, SVW observing platforms in space. A comparison of the evolutions of several low-pressure systems during the brief period when 2 SeaWinds systems were available on QSCAT and Midori-2 will demonstrate the impact of the second observing system on synoptic temporal resolution in SVW data.

Synoptic resolution also implies that high winds, often associated with raining systems, should also be represented in the SVW dataset used to force ocean models. We will present evidence that for wind speeds greater than about 15 ms$^{-1}$, valid SVW can be retrieved even in the presence of rain. From the synoptic perspective, a more permissive rainflag approach of this kind results in better representations of the large-amplitude wind stress curl events that can have the largest impacts on ocean model general circulation simulations.

### 3 Ensemble SVW Applications in Ocean Modelling

We will review global and regional ocean model sensitivities to high-wavenumber wind-forcing based on SVW observations from space. Many of these studies are cast in so-called “identical twin” experiments wherein only surface wind-forcing data sets are varied and differences in the model response are presumed to be due to this variation. Experiments of these kinds provide essential evidence to guide ocean model developers toward more realistic simulations of the target ocean circulations. But experimental results can be model dependent and quantification of the uncertainty in a given model response is a valuable additional piece of information that can be obtained through novel applications of SVW data from spaceborne platforms.

#### 3.1 SVW ensembles and ocean model response uncertainty

Following on experience in weather-forecast models, ocean model uncertainty can be characterized by the time-dependent variance computed from an ensemble of model integrations over the same period and domain. Uncertain situations lead to large ensemble spread or high ensemble variance, and more predictable model evolutions exhibit tighter ensemble spreads. Ensemble methods are expensive (i.e. one model integration for each ensemble member), and it is desirable to optimize ensemble size while insuring that realistic physical variance is well-represented. Ensemble generation methods receive considerable attention in the weather and climate forecast research community.

Ocean model ensemble methods are relatively less-well explored, but abundant, precisely characterized SVW data might lend efficiencies to this approach not available in atmospheric models. The precisely characterized error properties of SVW from spaceborne systems are well-documented in the literature (e.g. see Freilich and Vanhoff, 2005 and papers cited therein). These characterizations, and the abundant within-swath data can be used to form well-defined Likelihood Distributions to quantify the probabilistic properties for SVW retrievals.

Recent research in Bayesian Hierarchical Modelling (BHM) interfaces likelihood distributions with Prior Distributions based on relevant, but approximate, physical models for the particular system of interest, to derive Posterior Distributions for the SVW fields. BHM have been developed and extended for tropical winds in the Indian and western Pacific oceans (Wikle et al., 2001; Hoar et al. 2003). Figure 3 depicts a time series of SVW
distributions for the zonal wind component at a single point in this domain.

We have embedded 50 members of the SVW from the tropical BHM implementation into the standard forcing fields for the NCAR global ocean model. An ensemble of ocean simulations span a period containing a Madden-Julian Oscillation and its associated westerly wind bursts (WWB). A goal of this effort is to quantify the uncertainty in ocean model response to WWB in the western Pacific. We will examine the progress to date on this investigation.

4 References


Figure 1: Surface Wind Kinetic Energy, Mediterranean Sea. Annual average kinetic energy vs. wavenumber spectra for surface winds from ECMWF and NCEP analyses, and QSCAT, for 2000 through 2003. Bootstrap confidence intervals are indicated on the spectra for 2000; they are representative of confidence intervals in all years. Spatial scale in km is indicated on the axis at the top of the figure.
Figure 2: Global, annual average (2004) distribution of wavenumber power spectral density slope for the zonal component of the surface wind as retrieved from QuikSCAT. Wavenumber spectra are computed, using nested wavelet bases, in 8° squares that tile the globe.
Figure 3: Four-times daily histograms of zonal velocity at 150.25°E, 0.25°N, beginning on 5 January 2002. Zonal velocity realizations are part of a 50-member ensemble generated from the posterior distribution of a tropical surface wind BHM (Wikle et al. 2001; Hoar et al. 2003). QuikSCAT updates in this region usually occur before posterior distribution output times indicated by blue and gold histograms (most peaked distributions) each day. Histogram means and standard deviations are projected on the roof of the diagram for each output time.