Decomposition of surface drifter observations in the Atlantic Ocean

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[1] Surface drifter observations are decomposed into mean, seasonal (annual and semiannual) and eddy components via Gauss-Markov estimation. This approach helps separate seasonal fluctuations and mean values in the observationally-sparse tropical and South Atlantic, where monthly mean values cannot be calculated at the spatial scale of the major currents. In some regions, large differences are found between these means and those obtained by simple binned averaging. The differences are attributed to inhomogeneous sampling of seasonal variability, and to the inherent bias of Lagrangian observations towards periods of low velocity. The analysis reveals strong seasonal variations of some surface currents, including a significant late spring reversal of the western North Equatorial Counter-Current. *INDEX TERMS:* 4532 Oceanography: Physical: General circulation; 4227 Oceanography: General: Diurnal, seasonal, and annual cycles; 4594 Oceanography: Physical: Instruments and techniques. **Citation:** Lumpkin, R., Decomposition of surface drifter observations in the Atlantic Ocean, *Geophys. Res. Lett.*, *30*(14), 1753, doi:10.1029/2003GL017519, 2003.

1. Introduction

[2] Oceanic fluxes are usually examined in the framework of a decomposition in which a record $y(t)$ is divided into mean and eddy components, $y(t) = \langle y \rangle + y'(t)$. Ergodicity must be assumed to replace the expectation operator $\langle\rangle$ with an average, e.g., the mean of all observations within a spatial bin. However, sparse, autocorrelated observations and the broad-band energetic nature of the eddy component, dominated by mesoscale and seasonal fluctuations, make reliable decomposition estimates from ocean data a daunting task.

[3] Satellite-tracked drifters [*Sybrandy and Niiler*, 1992] provide direct measurements of currents and SST throughout much of the world's oceans, offering a unique tool to examine processes such as mean and eddy transport of momentum and heat. Drifters are often treated as moving current meters. Lagrangian displacements are averaged in bins to produce pseudo-Eulerian maps of mean currents, and removal of this mean yields estimates of the eddy fluctuations. A similar procedure can be applied to drifter-observed SST. The primary strength of this binning technique is its simplicity–it requires no explicit assumptions for the structure of the mean or residual fields, although implicit assumptions are made when choosing bin size. More sophisticated methods [*Davis*, 1985; *Bauer et al.*, 1998] have been constructed to address spatial variations of the mean.

[4] All methods of mean/eddy decomposition require some assumptions regarding the residuals. For example, all assume that variations about the mean are stationary - in the simple binned method, this assumption is implicit when estimating the appropriate degrees of freedom for the quarter-day-interpolated observations within a bin. However, in addition to the mesoscale eddy field, the observations may contain a diagnosable fluctuation at a considerably longer period: the seasonal cycle. Can we neglect seasonal variations of currents and SST when performing a mean/eddy decomposition? Seasonal variations may bias a pseudo-Eulerian mean estimate when two necessary conditions are met: (1) observations sample one season more heavily than others, and (2) the seasonal cycle's amplitude is a significant fraction of the mean. We should answer "no" to the above question in regions where these conditions apply. But where might such regions be located?

[5] *Condition 1:* In the Atlantic Ocean, *Fratantoni* [2001] showed that the overall ensemble of drifter observations is nearly homogeneously distributed through the seasons. However, this is not true in smaller regions, e.g., the 1° square bins in which mean and eddy amplitudes are often calculated. To demonstrate this, the quarter-day-interpolated positions of all drogued Atlantic drifter observations prior to 1 August 2002 were assigned a complex number, with unit amplitude and phase set by the yearday (0° for 1 January, 180° for 30 June, ctc.). These were averaged in 1° bins to produce maps of the potential seasonal observation bias (Figure 1). An amplitude near zero indicates nearly homogeneous sampling through the seasons; amplitudes near unity show where one season is sampled exclusively. Nearly two-thirds of the bins exceed an amplitude of 0.3; past this threshold, bootstrap subsampling of a simulated signal (equal mean and annual amplitude and known true mean) yields a significantly biased estimated mean.

[6] *Condition 2:* SST has a well-known annual cycle in the subtropics. Tropical currents are suspected to display strong annual and semiannual variations [*Stramma and Schott*, 1999]. Previous studies of tropical Lagrangian observations have addressed this by subsetting the data for a particular season, e.g., the four seasonal maps of tropical Pacific currents of *Bauer et al.* [2002]. However, this approach discards the time-mean information of *all* the observations in a region, thus eliminating degrees of freedom which could be used to simultaneously estimate the mean, seasonal signal and residuals. The density of observations in much of the tropical Pacific is relatively large, so the discarded degrees of freedom are not crippling. This is not true in the tropical Atlantic, where a "summer" map (for example) would contain many bins with too few observations to estimate the summer-mean values.

2. Methodology

[7] A decomposition of 2-day low-passed velocity and SST drifter observations was performed via Gauss-Markov

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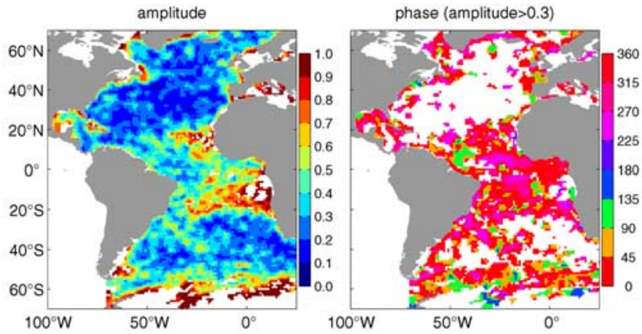

Figure 1. Amplitude of the seasonal observational bias (left panel) and the corresponding phase (degrees; right panel). Phase not shown where amplitude is smaller than 0.3.

estimation [*Bretherton et al.*, 1976]. In this approach, observations within a bin are treated as a time series $y(t)$ composed of a mean, cyclical components, and residual $n(t)$ according to

$$y = x_o + \sum_{i=1}^{2} \left[x_1^s \sin\left(\frac{2\pi t}{P_i}\right) + x_1^c \cos\left(\frac{2\pi t}{P_i}\right) \right] + n, \qquad (1)$$

where P_i is the period of the seasonal harmonics (annual and semiannual). In matrix formulation, the full set of observations within the bin becomes $\mathbf{y} = \mathbf{A}\mathbf{x} + \mathbf{n}$, where $\mathbf{A}$ contains the coefficients for the unknowns x_o, x^c and x^s contained in vector $\mathbf{x}$. The Gauss-Markov estimator for $\mathbf{x}$ is

$$\tilde{\mathbf{x}} = \mathbf{R}_{xx}\mathbf{A}^{\mathrm{T}}\left(\mathbf{A}\mathbf{R}_{xx}\mathbf{A}^{\mathrm{T}} + \mathbf{R}_{nn}\right)^{-1}\mathbf{y}, \qquad (2)$$

[c.f., *Wunsch*, 1996], where $\mathbf{R}_{xx}$ is the covariance matrix of the unknowns and $\mathbf{R}_{nn}$ is the variance structure of the eddy noise $n(t)$. The method produces posterior estimates of the covariance structures of $\mathbf{x}$ and $\mathbf{n}$, allowing generation of formal error bars for the amplitudes $\mathbf{x}$ and maps of the resolution of these amplitudes. For this study, diagonal elements of $\mathbf{R}_{xx}$ were assumed to be equal to the squared range of $y(t)$, off-diagonal elements were set to zero, and elements of $\mathbf{R}_{nn}$ were given by

$$R(\tau) = \mathrm{std}(y)^2 \cos(\pi\tau/2T_d) \exp\left[-\left(\pi\tau/2\sqrt{2}\, T_d\right)^2 \right] \qquad (3)$$

[*Garraffo et al.*, 2001a; *Lumpkin et al.*, 2002] with T_d = 10.33 days, consistent with an integral eddy time scale of five days. As a consequence, observations separated by less than five days do not affect the estimated $\mathbf{x}$ and its error bars as if they were separated by 50 days (unlike in a simple binned average).

[8] Two caveats of this approach demand mention. First, the seasonal signal is assumed to be captured to lowest order by an annual and semiannual harmonic. At basin scales, these two harmonics account for ~70% of the seasonal variance [*Richardson and Walsh*, 1986]. However, if there are regions with energetic higher-frequency harmonics, errors may result "when decomposing the observations as in (1)." Second, in addition to mesoscale fluctuations, the residual $n(t)$ will include interannual variations where the observations can resolve them. Where they cannot, interannual variations may bias the mean values. For example, the equatorial Pacific is most heavily sampled by surface drifters during El Niño-related warming events, requiring regression onto an ENSO index to yield unbiased mean current estimates [*Johnson*, 2001].

3. Results

[9] When applied to the Atlantic surface drifter observations, the Gauss-Markov (GM) decomposition produces reasonable fields of mean, seasonal, and eddy currents and SST, and formal error bars on all components. Mean SST from the decomposition is closer to climatology than bin-averaged SST, and SST annual and semiannual amplitudes and phases are broadly consistent with monthly NCEP and COADS fields (Figure 2). The drifter observations suggest a significantly stronger semiannual amplitude in the South Atlantic. The maxima of this semiannual cycle are aligned with the maximum and minimum of the annual cycle, suggesting a sharper summer SST maximum and a broader winter SST minimum than in the climatology.

[10] Differences between binned means and GM-derived means (Figure 3) are small throughout much of the domain, demonstrating the robustness of pseudo-Eulerian maps derived via simple binned averaging. However, the differences are large where the annual and observation bias amplitudes (Figure 1) are large. In addition, the GM method yields a stronger Gulf Stream (Figure 3): at 73°W the maximum mean drifter speed from the GM method is 95 cm/s, while the binned mean is 75 cm/s. An Eulerian average constructed

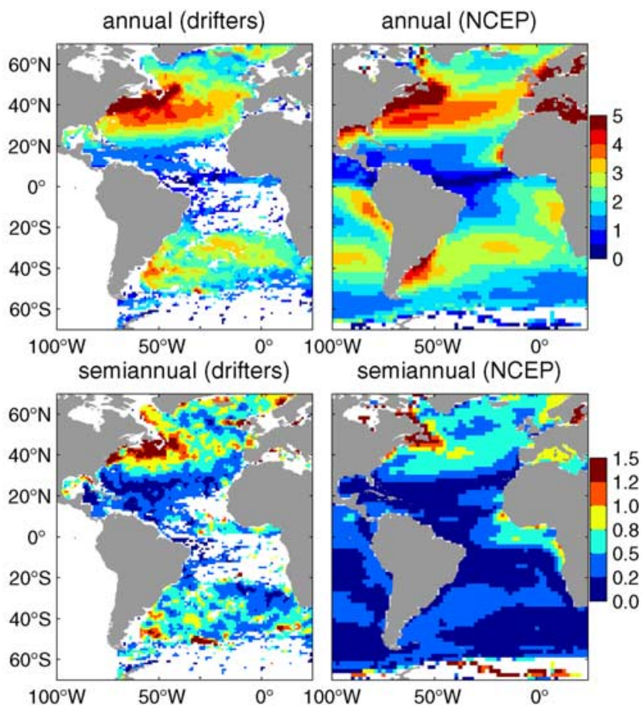

Figure 2. Amplitude (°C) of the annual (top) and semiannual (bottom) variations of SST calculated from drifter observations (left) and from NCEP monthly climatology (right).

from 19 velocity profile sections [*Rossby*, 1987] reveals a mean Gulf Stream with an approximately Gaussian cross-stream velocity profile, with a peak speed of $\sim$120 cm/s and an e-folding scale of 60 km. Averaged over 1°, this profile suggests that an unbiased mean should be 100–110 cm/s. The difference between the GM-derived mean and the binned mean in the Gulf Stream is not due to seasonally-biased observations, but instead due to the five day integral time scale which defines independent observations in the GM method. The difference between binned and GM means in the Gulf Stream vanishes for $T_L \rightarrow 0$, with or without including the seasonal harmonics in the decomposition; it can be replicated by bin-averaging the observations after resampling them at a five day interval. If the Gulf Stream meanders into and out of a bin, it would cause the spatially-averaged speed in the bin to vary from, say, 25 cm/s to 75 cm/s, with a temporal mean of 50 cm/s. At 25 cm/s, a drifter crosses a 1° bin in five days; at 75 cm/s, it takes less than two days. Even with perfectly homogeneous sampling through the seasons, more observations are made within the bin during low-speed times—the binned mean is biased low. This bias has been demonstrated in MICOM simulations, where the true Eulerian mean is significantly larger than the binned mean of simulated Lagrangian observations in the Gulf Stream [*Garraffo et al.*, 2001b].

[11] The distribution of seasonal current amplitudes and phases is qualitatively consistent with an analysis of historical ship drifts [*Richardson and Walsh*, 1986], although maximum amplitudes are larger by a factor of 1.4–1.5 even after smoothing on the $2° \times 5°$ grid of the ship drift study. By combining the mean currents with the amplitudes and phases of the seasonal components, time series of the seasonal variability may be constructed. Encouraging results include spatial coherence of seasonal variations over many independent bins, not enforced a priori by the analysis. Specific features of the seasonal variability include a Boreal spring reversal of the western North Equatorial Counter-Current and a summer reintensification [*Garzoli and Katz*, 1983] and

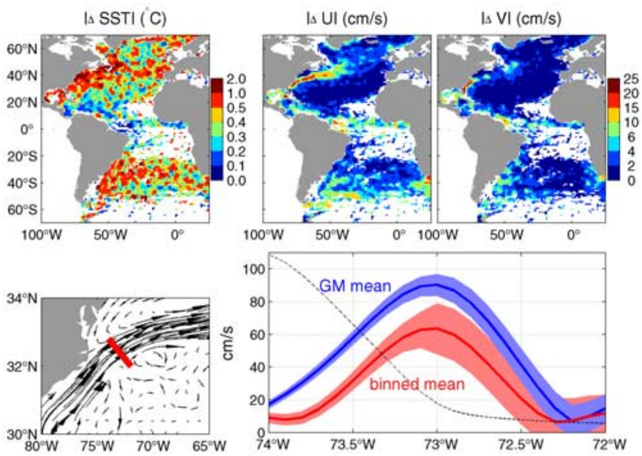

Figure 3. Top: absolute difference between binned and GM-derived mean fields of SST (left), zonal speed (center) and meridional speed (right). Bottom: profile of mean net speed across the Gulf Stream (path indicated in left panel) given by the two methods. Black dashed line: tens of drifter days used for calculation of mean.

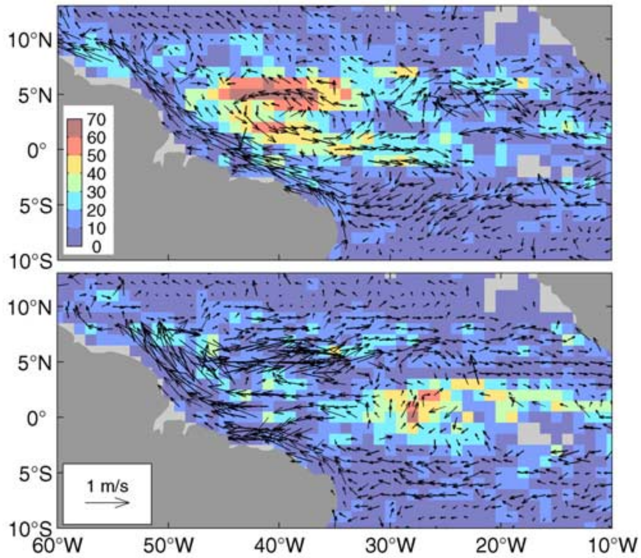

Figure 4. Top: mean, annual and semiannual currents for 1 May. The amplitude (cm/s) of annual zonal speed fluctuations is shaded. Bottom: mean, annual and semiannual currents for 1 October. The amplitude of semiannual zonal speed fluctuations (cm/s) is shaded.

concurrent variations in the strength of the North Brazil Current retroflection [*Johns et al.*, 1998], northwestern South Equatorial Current, and Guyana Current (Figure 4).

[12] The value of an improved mean/eddy decomposition should not be understated. Drifters provide direct observations of concurrent velocity and SST, allowing estimates of momentum and heat advection and the evolution of oceanic fronts, and, as observations accumulate, providing insight into climate signals—but all these estimates may be contaminated by seasonal variations and biased mean estimates without careful treatment. Recent studies [*Grodsky and Carton*, 2001; *Niiler et al.*, 2003] combine altimetric- and drifter-derived velocities; comparison of their seasonal amplitudes with the drifter-only fields derived here could provide insight for evaluating how successfully seasonal thermal expansion has been resolved in the sea level anomaly record. More details of this study's results will be presented in a follow-up paper, including an examination of the residual eddy field, mean and eddy surface fluxes, and the seasonal variations of advective pathways.

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