

## ***Interactive comment on “On the characteristics of sea ice divergence/convergence in the Southern Beaufort Sea” by J. V. Lukovich et al.***

**J. V. Lukovich et al.**

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Dr. Christian Haas Editor, The Cryosphere November 20th, 2014

Dear Dr. Haas:

Thank you for your suggestions and supplementary material. Please find below responses to reviewers' comments on the manuscript "On the characteristics of sea ice divergence/convergence in the Southern Beaufort Sea", by J.V. Lukovich, D.G. Babb, R.J. Galley, R.L. Raddatz, and D.G. Barber, manuscript number tc-2014-117, in italicized text. Responses to referee's comments will also be provided separately in response to the individual referee suggestions and recommendations.

General comments The authors would like to thank the editor and three reviewers for  
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helpful comments and suggestions. Effort has been made to improve the quality of the figures, emphasize the focus of the study on differences in sea ice convergence and divergence near the pack ice edge and interior, emphasize the applicability of the triplet approach to an understanding of sea ice deformation, and to improve clarity in the manuscript. Please find below specific responses to the Reviewer's comments and suggestions.

### Responses to Referees

Anonymous Referee #3 Summary This manuscript presents an analysis of the drift of 11 buoys deployed on sea ice in the Southern Beaufort Sea shortly before the annual extent minimum in 2009. The authors group these 11 buoys into 5 triplets, with two 4-buoy pairs. By analyzing the changes in the shape and area of the triangles formed by these triplets, the authors identify periods of convergence and divergence during which the response of the buoy triplet respond differently depending on their proximity to the ice edge and the coast. Unfortunately, the manuscript is written in such a way to defy further summarization. As well as incoherent punctuation and ambiguous use of terminology, the authors repeatedly fail to clarify confusing references to the positions at different times of specific triplets, which makes it difficult to follow the intended line of reasoning. It would help if the figures were legible but poor design and an absence of error bars increase the challenge for the reader. I also have serious concerns about the suitability of the authors analytical approach for such highlight elongated triplets, which I apparently share with at least one other reviewer. On face value, this manuscript has the potential to make significant and interesting contributions to our understanding of ice transport and deformation in the Beaufort Sea, but in its current state it has serious problems that will take significant effort to rectify. Thank you for your helpful comments and suggestions. The authors have made a concerted effort to address issues related to punctuation and ambiguity in terminology in the revised manuscript. Distinction has also been made between the initial identification of triplets based on their position relative to the coastline, and positions of triplet centroids relative to the

dynamic reference frame of the ice edge to highlight differences in sea ice divergence and convergence near the pack ice edge and interior. As is noted in response to the first reviewer's comments, the quality of the figures has been improved to ensure that they are legible and illustrate key features in centroid evolution, and error bars included for triplet areas in Figure 3. The suitability of triplet area to measure sea ice divergence and convergence is addressed through description of the stabilized Heron's formula to avoid singularities for elongated triplets; triplet E has also been excluded from the analysis to focus on sea ice deformation near the pack ice edge and interior. Please find below responses to specific comments. General Comments 1. Use of highly elongated triangles for calculating changes in area Reading the discussion on this paper so far, it appears I share the same concern as the other reviewer regarding the use of such highly elongated triplets for calculating divergence. In particular, triplets with such configuration are prone to "turning inside out" and violating the implicit assumption that ice does not pass between the vertices of the triangle formed by the triplet. Indeed, the authors note themselves on p. 4292 lines 12-13 that the beacons in triplet C became "interchanged", demonstrating that such behavior is commonplace. The highly elongated triangle associated with triplet E has been removed from the revised manuscript in order to focus the study on sea ice divergence and convergence in the pack ice and in particular on differences in sea ice deformation near the pack ice edge and interior. Although fluid can be mixed in and out of the triangle, elongation of triplets illustrates filamentation associated with shear, such as if found at the periphery of the Beaufort Gyre. By contrast, a subsequent increase illustrates the emergence of conditions that increase spatial variability and increases in the inter-beacon distances. Please see also responses to the first comment provided by the first referee. 2. Reference to the position of triplets with respect to "distance from the continental coastline and pack ice edge" At the risk of sounding obtuse, this is a highly confusing reference frame to use. First, the ice edge evolves through the study period while the coastline is remains fixed and, second, due to the shape of ice edge, some triplets can be further from the coastline, yet closer to the ice edge than others. Why do the authors try to use both

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reference frames? To make matters worse, in some cases the text contains references to the westernmost or southernmost ice edges. The authors could help the reader by clarifying which triplets they are referring to, but they consistently fail to do so. Moreover, despite the repeated references to variations in the convergence/divergence with distance from these edges, the reader is not presented with any table or graph providing the actual distances. The authors agree that reference to the position of the beacon triplets relative to both the ice edge and coastline confounds interpretation of sea ice divergence and convergence in the context of a fixed and moving reference frame. In light of the present referee's comments, the authors have sought to distinguish between the role of the continental coastline as a fixed reference used to initially identify the beacon triplets and categorize them according to distance from the continental coastline, and the role of the ice edge as an evolving reference for the measurement of differences in sea ice deformation near the pack ice edge and interior. Additional text has also been included in the Methods section to distinguish between reference to the continental coastline and ice edge, as follows: "It should be noted that triplets are initially identified relative to the fixed reference of the coastline. However their evolution and in particular sea ice divergence and convergence are investigated relative to the dynamic frame of the pack ice edge to investigate differences in dispersion at the pack ice edge and interior." 3. Use of punctuation I recommend the authors review some basic rules of punctuation usage, such as when and how to use semi-colons and parentheses and how to construct sentences without requiring ambiguous uses of commas. For guidance on parentheses in particular, I encourage the authors to read the following EOS article: Robock, A. (2010), Parentheses are (Are Not) for References and Clarification (Saving space), *Eos Trans. AGU*, 91(45), 419-419, doi:10.1029/2010E0450004. Thank you for the suggested reference. Effort has been made to improve punctuation in the revised manuscript following the recommendations outlined in Robock (2010, and to limit the use of parentheses in the description of results and their assessment. 4. Use of elongated and stretched The authors use elongated and stretched interchangeably throughout the manuscript. Elongated is the more appropriate term and I recommend

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the authors use it in favor of stretched in all cases. The authors have replaced the term stretched with elongated throughout the manuscript where appropriate. Specific comments P4282 Line 4: replace “true” with “important”. This has been changed. Lines 7 – 9: The use of the word “defined” here is very confusing. Please clarify what is defining what, or use a different word. This word “defined” has been replaced with “initially identified” to clarify triplet categorization based on their distance from the coastline. Lines 9 – 11: Between “illustrate” and “demonstrate” there’s some redundant text that could be removed here. This sentence has been clarified so that it now reads as “Results from this analysis illustrate differences in the evolution of ice beacon triplets at the periphery and interior of the ice pack in the SBS.” P4283 Line 25: Replace “thickness” with “thickening”. This has been corrected. P4284: Lines 21 – 26: These lines would be much better written as three separate sentence rather than forced into a awkward semi-colon separated list. Also, the authors should explain the meaning and significance of terms such as elliptic or hyperbolic. These lines have been rewritten as three separate sentences, and the significance of elliptic and hyperbolic included. This section now reads as follows “Previous studies have highlighted the role of forcing (namely wind stress) and coastline geometry in establishing lead patterns/fractures in the ice cover captured by sea ice deformation (Pritchard, 1988; Overland et al., 1995; Hutchings et al., 2005, 2011). Overland et al. (1995) demonstrated that in the Beaufort Sea for spatial scales exceeding 100 km the sea ice cover moves as an aggregate. For scales between 1 km and 100 km the ice cover moves as an aggregate or discrete entity based on whether an elliptic (homogeneous) or hyperbolic (discrete) regime is established relative to the coastline, providing a characterization of ice-coast interactions. More specifically, an elliptic regime is characterized by diffusive behavior and spatial homogeneity in the ice pack, in contrast to a hyperbolic regime that is characterized by propagation of discontinuities and directionality in the ice pack (Overland et al., 1995). Furthermore, for spatial scales on the order of 1 km the ice cover is characterized by floe, or ice-ice, interactions.” Line 22: replace “less than 100 km” with “between 1 km and 100 km”. This has been changed. Please see also previous comment.

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P4286 Lines 10 – 24: The last paragraphs of the introduction read like they were taken straight out of a grant proposal. It does not behoove the authors to appear to be trying to sell something to the reader. The authors have removed some of the text from the last section of the Introduction to address this concern. The last paragraph of the Introduction is now written as “Recent studies of sea ice motion in the marginal ice zone (MIZ) in the southern Beaufort Sea (SBS) analyzed ice beacon trajectories during the fall/winter of 2007/2008 as part of the International Polar Year Circumpolar Flaw Lead study based on absolute, or single-particle dispersion statistics to provide a regional account of sea ice dynamics (Lukovich et al., 2011). Results from this investigation highlighted the existence of two scaling law regimes, namely in the zonal direction characteristic of westward advection and in the meridional direction characteristic of a hyperbolic (strain-dominated) regime and quasigeostrophic turbulence (Lukovich et al., 2011). Coherent ice drift features associated with mesoscale ice dynamics, namely loop and meander reversal events in the SBS were also investigated through analysis of relative (two-particle) Lagrangian dispersion statistics (Lukovich et al., 2014). In the present study we examine smaller-scale features and deformation characteristics of sea ice motion in the SBS based on a three-particle analysis that monitors evolution in a triangular array of ice beacons during the fall of 2009. In particular, a triplet analysis is used to provide insight into sea ice convergence and divergence at the pack ice edge and interior that is essential to an accurate representation of sea ice dynamics in modeling studies and to our understanding of the role of sea ice dynamics in ocean-sea-ice-atmosphere interactions. In consideration of these objectives, we therefore examine the following research questions: 1. What is the evolution in area of ice beacon triplets during the fall of 2009? (Sea ice convergence and divergence) 2. Is sea ice deformation in fall 2009 governed by ice and/or atmospheric forcing? How is this evolution influenced by triplet proximity to the pack ice edge? (Sea ice and atmospheric forcing)”

P4287 Lines 16 – 17: Changes in aspect ratio do not necessarily imply changes in area. In fact in the previous sentence the authors just explained this.

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The authors agree. The aspect ratio does however reflect changes in shape, and “area” has been changed to “shape” to reflect this.

Lines 23 – 25: How can an increase in area be related to non-divergent flow? An increase in area can be related to non-divergent flow through displacements superimposed on the mean flow in response to external factors such as surface winds. In response to the comments of both the present and first referee, text has been included in the revised manuscript that reflects this:

“Non-conservation in area may be attributed to either divergent surface flow or, as has been demonstrated in previous drifter studies, random perturbations superimposed on the mean flow (LaCasce and Ohlmann, 2003; LaCasce, 2008).

The sentence on lines 23 – 25 of the original manuscript has also been revised and now reads:

“Both studies depict a monotonic increase in triplet area characteristic of displacements in response to wind forcing rather than divergent surface flow, the latter of which would be captured by both positive and negative divergence resulting in decreases in the triplet area (LaCasce and Ohlmann, 2003).

P4291 Lines 16-19: There is some serious punctuation abuse in this sentence. Between the parentheses, parenthetical commas, and commas in series, it is difficult to read this sentence in one sitting. Consider re-writing without parentheses and using as many separate sentences as necessary.

This sentence has been revised and separated into two. The rewritten text is as follows:

‘Values of  $\sim 1.7$  are found for beacons 9, 10, and 11 that comprise triplet D. This is in contrast to values of  $\sim 1.3$  for beacons at lower latitudes, indicating more erratic ice drift at higher latitudes in the SBS in the fall of 2009.’

P4295 Lines 19-22: This is not appropriate use of punctuation. Rewrite without colons and semi-colon. E.g:

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Comparison of centroid velocities highlights intervals when sea ice in the SBS is governed either by non-local mechanisms, in which case it moves as a consolidated aggregate, or local mechanisms when it moves as a fractured ice cover governed by local interactions.

Thank you for the suggested revisions. This sentence has been changed.

Line 24: Why are these not listed in chronological order?

The dates are now listed in chronological order.

P4304 Line 20: What is the parenthesized “(closest to)” supposed to refer to?

This sentence has been revised as follows:

“It is further shown that triplet area evolution is depicted by decreasing coherence with increasing latitude, evident in triplet base length scales of  $\sim 70$  km, 30 km, and 20 km for triplets B, C, and D respectively from mid-September to October.”

Figure 1a: This figure present highly important information for the reader, yet the key details are rendered too small to be of much use.

As previously noted, the authors have made a concerted effort to improve the quality of the figures and their legibility.

To make better use of space and avoid the problem of having some beacons form parts of multiple triplets, I recommend the following changes: 1) Plot the trajectories for the triplet centroids rather than the individual beacons. 2) Instead of using different symbols to indicate the triplet configurations on specific dates, connect appropriate beacon locations with colored (perhaps dashed) lines corresponding to the appropriate triplet. 3) Less text should be needed in the legend, so the authors should now be able to use a larger fontsize.

Figure 1a is now included as Figure 1b, and following suggestion 1) now illustrates the beacon centroids. The triangular configurations are also indicated for specified dates

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in colors associated with the appropriate triplet, and larger font size included in the legend for the triplet labels. Please see the attached supplementary material providing the revised figures.

Figure 1b: I recommend the authors choose a different color scale for the ice concentration to avoid clashing with the colors used for the beacon drift paths.

Thank you for this suggestion. Sea ice concentrations are now presented in greyscale in Figures 1a and 9.

Figure 3: Error bars would be helpful for understanding the significance of the variability in this figure.

Error bars are now included in this figure for all triplets.

Figure 4: This figure wastes a lot of white space and reproduced at such low resolution that zooming in to see the details does not help greatly.

The resolution for this figure has been improved and the range for the y-coordinates for both panels reduced so as to eliminate white space.

Figure 6: Same comment as for Figure 4.

This figure now depicts the full time series and an enlarged version of the first interval for enhanced divergence/convergence. The resolution has also been increased.

Figure 8: The text is too small in this figure.

The font size has been increased for this figure.

Figure 9: Same comment as for Figure 1b.

As previously noted, greyscale contours have been used for sea ice concentration maps in the revised figure.

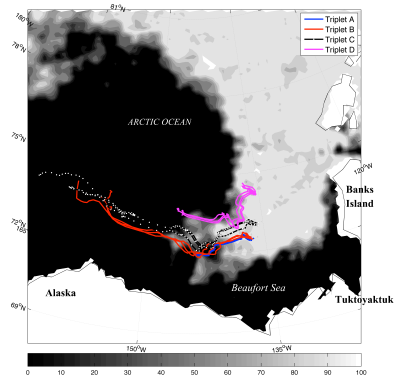
Please find attached as well the scaled figures as the original figures were included in the initial response.

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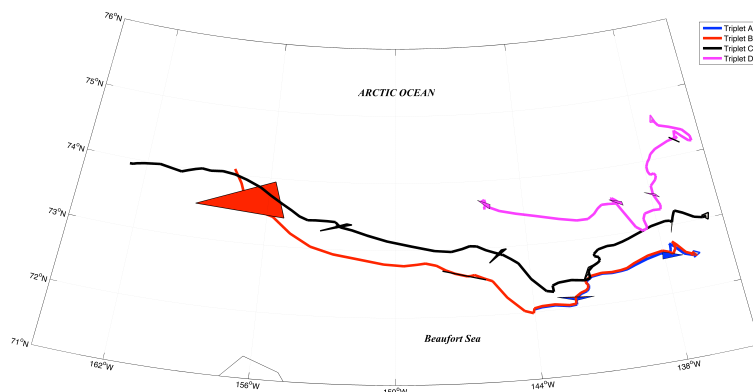
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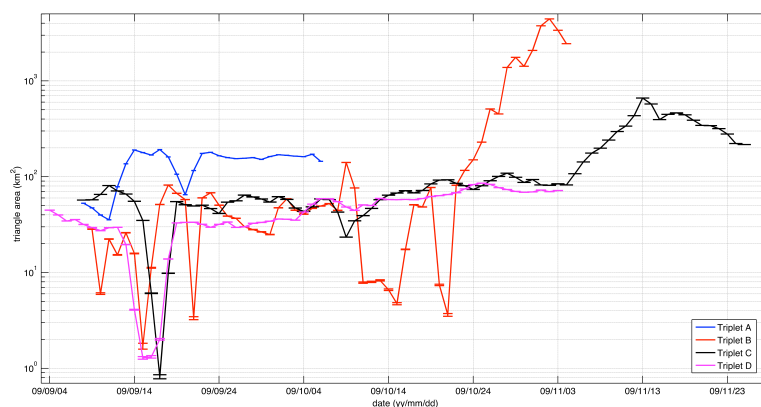
**Fig. 1.** Figure 1a. Map of study area and winter 2009/10 beacon trajectories superimposed on AMSR-E sea ice concentrations for September 9th, 2009 and depicting the marginal ice zone on deployment.

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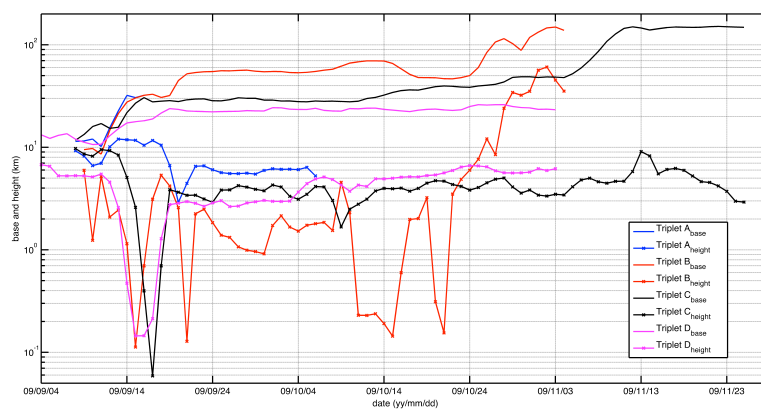
**Fig. 2.** Figure 1b. Map of study area and winter 2009/10 beacon trajectories. Blue, red, black and magenta indicate triplets A, B, C, and D, respectively, with triplet A located nearest to the coastline, and t

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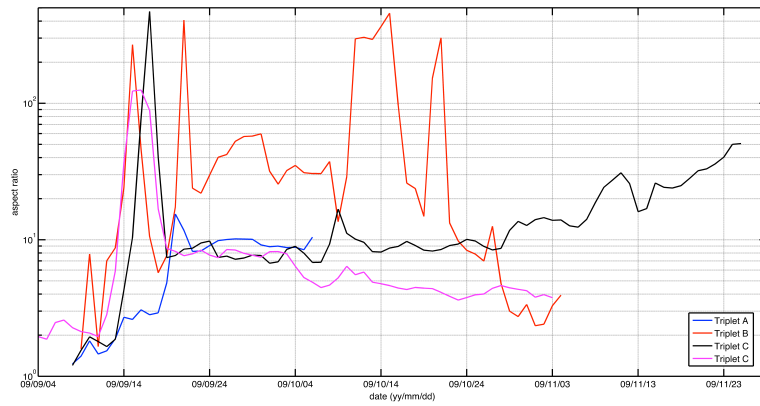
**Fig. 3.** Figure 3. Semilog plot of triangular area by date for ice beacon triplets A to D.

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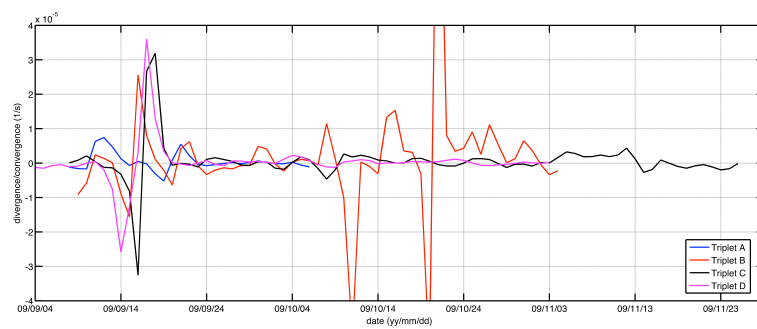
**Fig. 4.** Figure 4. Semilog plot of the triangle a) height and base, and the b) aspect (base-to-height) ratio as a function of date for triplets A to D.

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**Fig. 5.** Figure 4. Semilog plot of the triangle a) height and base, and the b) aspect (base-to-height) ratio as a function of date for triplets A to D.

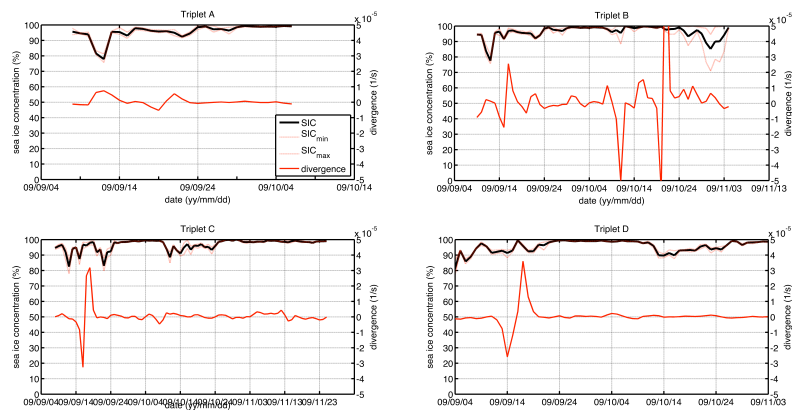
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**Fig. 6.** Figure 6. Evolution in sea ice divergence and convergence for triplets A to D from a) September 9, 2009 to November 12, 2009 and b) September 9, 2009 to October 4, 2009.

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**Fig. 7.** Evolution in mean (black solid line), minimum and maximum (red dashed line, left axis) sea ice concentrations, and divergence (red solid line, right-axis) within a  $\sim 25$  km triplet centroid ra

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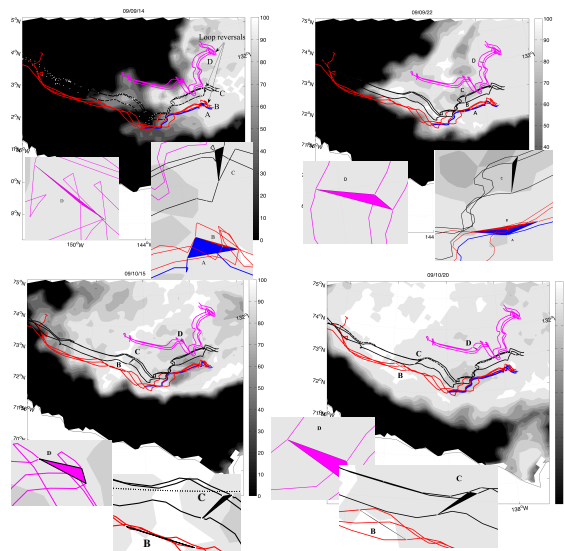


Figure 9. Ice beacon triplet trajectories superimposed on selected daily maps of SIC during intervals of enhanced divergence/convergence (September 14<sup>th</sup> and 22<sup>nd</sup>, and October 15<sup>th</sup> and 20<sup>th</sup>, 2009).

**Fig. 8.** Figure 9. Ice beacon triplet trajectories superimposed on selected daily maps of SIC during intervals of enhanced divergence/convergence (September 14<sup>th</sup> and 22<sup>nd</sup>, and October 15<sup>th</sup> and 20<sup>th</sup>, 2009).

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