Systematic Shift in Plume Bending Direction at Grotto Vent, Main Endeavour Field, Juan de Fuca Implies Systematic Change in Venting Output along the Endeavour Segment

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Abstract

Analysis of the time-dependent behavior of the buoyant plume rising above Grotto Vent (Main Endeavour Field, Juan de Fuca Ridge) as imaged by the Cabled Observatory Vent Imaging Sonar (COVIS) between September 2010 and October of 2015 captures long-term time-dependent changes in the direction of background bottom currents independent of broader oceanographic processes, indicating a systematic evolution in vent output along the Endeavour Segment of the Juan de Fuca Ridge. The behavior of buoyant plumes is a convolved expression of hydrothermal flux from the seafloor and ocean bottom currents in the vicinity of the hydrothermal vent.

Plume behavior can be quantified by describing the volume, velocity and orientation of the effluent relative to the seafloor. Using three-dimensional acoustic images by the COVIS system, we looked at the azimuth and inclination of the Grotto plume in 3 hour intervals and identified a bimodal shift in their bending from NW and SW to SE in 2010, 2011, and 2012 to single mode NW in 2013 and 2014. Modeling of the distribution of azimuths for each year with a bimodal Gaussian indicates that the prominence of southward bottom currents decreased systematically between 2010 and 2014.

Spectral analysis of the azimuthal data showed a strong semi-diurnal peak, a weak or missing diurnal peak, and some energy in the sub-inertial and weather bands. This suggests the dominant current generating processes are either not periodic (such as the entrainment fields generated by the hydrothermal plumes themselves) or are related to tidal processes. The surface wind patterns in buoy data at 2 sites in the Northeast Pacific and the incidence of sea-surface height changes related to mesoscale eddies show little systematic change over this time period.

Given the limited bottom current data for the Main Endeavour Field and other parts of the Endeavour segment, we hypothesize that changes in venting either within the Main Endeavour Field or along the Endeavour Segment have resulted in the changes in background currents. Previous numerical simulations (Thomsen et al 2009) showed that background bottom currents were more likely to be controlled by the local (segment-scale) venting than by outside ocean circulation or atmospheric patterns.

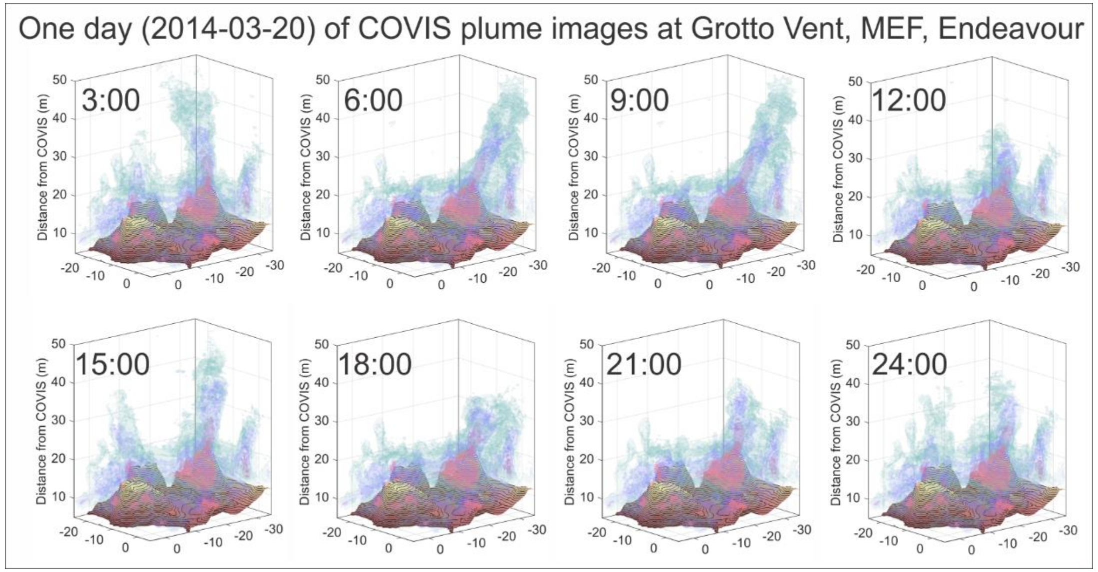
Plain-Language Summary:

Changes in the shape of the plume (fluids rising) above Grotto Vent at Main Endeavour Field on the Juan de Fuca Ridge were imaged by the Cabled Observatory Vent Imaging Sonar (COVIS) between September 2010 and October of 2015. They show long-term changes in the direction of background ocean bottom currents. The direction and amount such plumes are displaced by ocean bottom currents depends on both how fast the fluids rise from the seafloor and the ocean bottom currents in the area. We looked at the direction and amount of bending of the Grotto plume in 3 hour intervals and identified a shift from balanced north-to-south bottom currents to mostly southward bottom currents between 2010 and 2014. A detailed look at this and related data suggest that changes in overall venting either at other vents within the Main Endeavour Field or along the Endeavour Segment have resulted in the changes in background currents. This is consistent with previous modeling of the bottom current flow on the Endeavour Segment.

Box 1 – Motivation

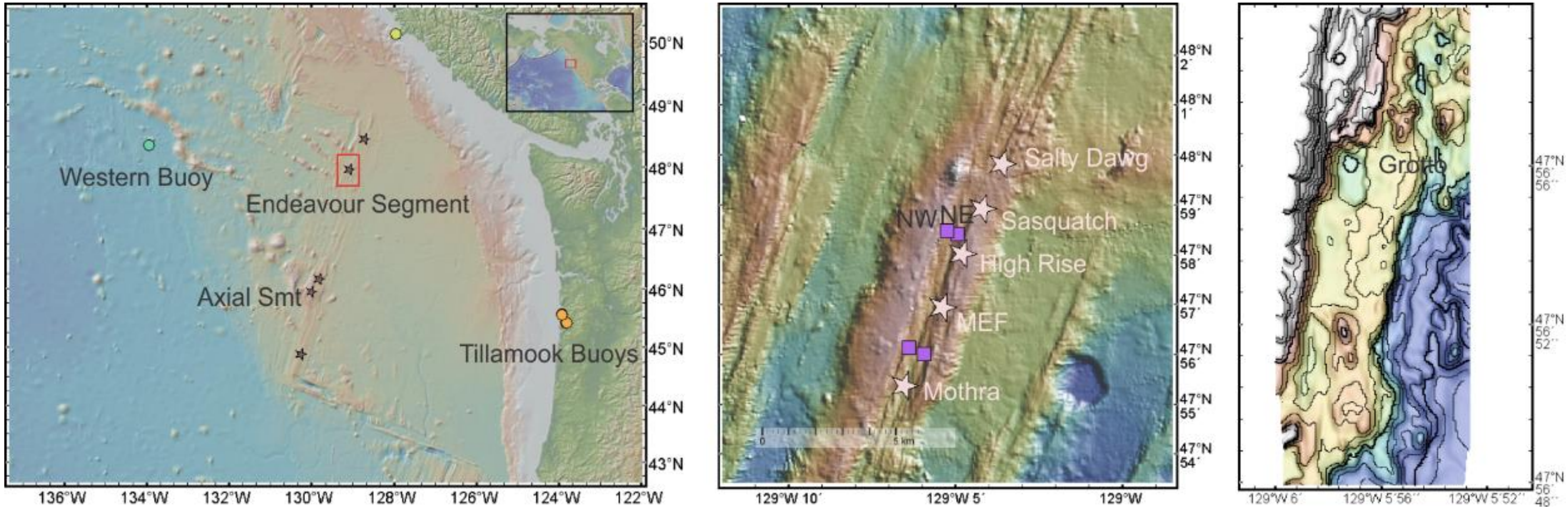
Previous observations of hydrothermal plumes in the Main Endeavour Field identified the influence of tides on plume behavior. Rona et al (2006) observed changes in plume bending direction over a 24 hr interval that were consistent with a semi-diurnal tidal cycle in bottom current direction and speed. Other studies (Burd and Thompson, 2019) have identified a neutrally buoyant plume between 1900-2100 m depth that varies in depth during the late summer and fall, suggesting a change in the balance between plume rise rate and bottom current speeds.

This study seeks to use a long-term (5 year) record of plume bending to deconvolve the influence of changes in local and regional hydrothermal flux from changes in the background currents. In particular, 5 years of observatory and remote sensing data will be combined to identify patterns and trends in ocean bottom currents within the Endeavour rift valley on the Juan de Fuca Ridge, identify the extent to which these patterns and trends may reflect trends in surface weather, and suggest alternative explanations of the observed changes.



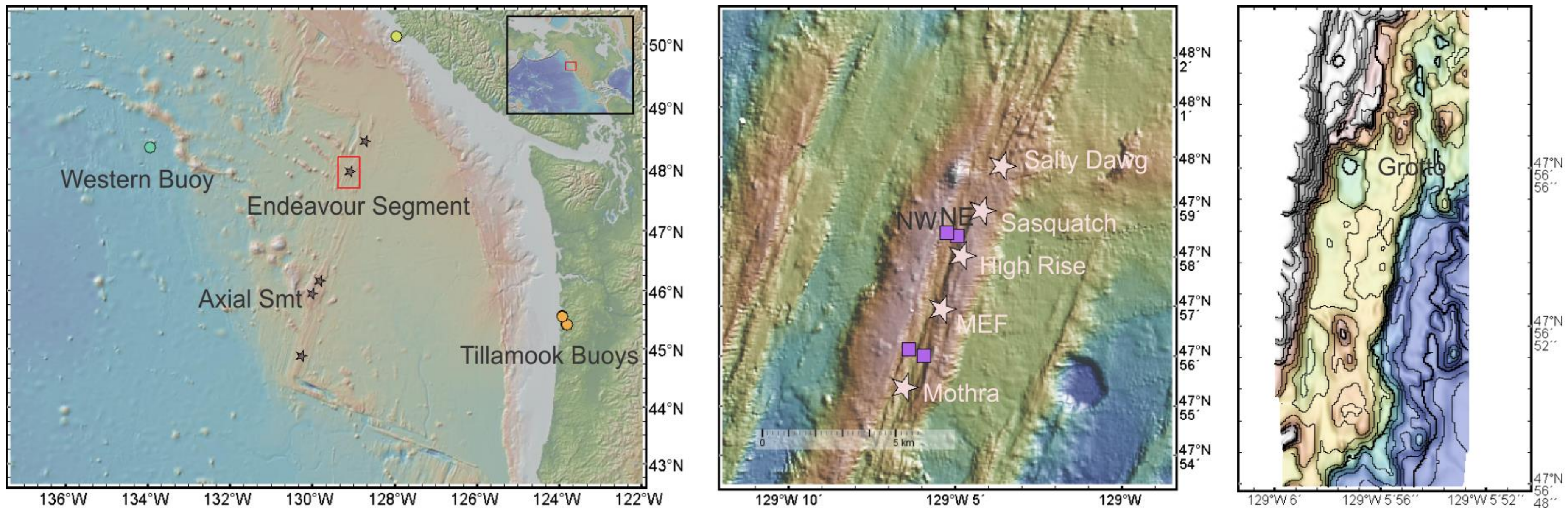
Box 1 – Motivation - continued

This study will show that plume bending at Grotto vent underwent a systematic shift in mean direction indicative of a shift in net background flow. Our observations suggest that monitoring one plume at Grotto vent within the Main Endeavour Field provides some insights into venting along the entire Endeavour segment. Acoustic monitoring of even single vents has the potential to provide larger scale implications for segment or seamount scale venting changes.



(a) Map shows location of the study site, the Endeavour segment, in relation to overall geography of the Pacific Northeast. Also shown are the location of the buoy data and SSH data used in this study. (b) Closer map of the Endeavour Segment shows the location of the vent fields and the moorings, whose current data is used. (c) Close up map of the Main Endeavour Field shows the location of Grotto Vent. The acoustic imaging sonar, COVIS, was imaging the plumes that rise above Grotto.

Box 2 – Background on Plumes



The Endeavour Segment of the Juan de Fuca Ridge is an intermediate spreading ridge located 250km offshore of Vancouver Island in the Northeast Pacific Ocean. As an Integrated Study Site for the Ridge 2000 program, the Endeavor segment is among the best studied areas of seafloor on Earth (see references in Clague et al., 2020). The central portion of the rift is a topographic high is cut by a 100- to 200-m-deep and 1km wide axial valley that hosts 5 major hydrothermal vent fields whose spacing along strike (Kelley et al., 2012, Haymon et al., 1991; Delaney et al., 1992; Von Damm et al., 1998) is a reflection of the subsurface convection systems (Kelley 2001). Depths for the segment range from 2100 to 2800 m and the ridge flanks are characterized by 300-m-high ridge parallel abyssal hills and a 200 m high plateau that has been shown to overlie thickened crust (Glickson et al., 2007, Karsten et al., 1986, Soule et al., 2017). Within the rift, the seafloor morphology is rough and dominated by pillow lava deposits and sulphide towers.

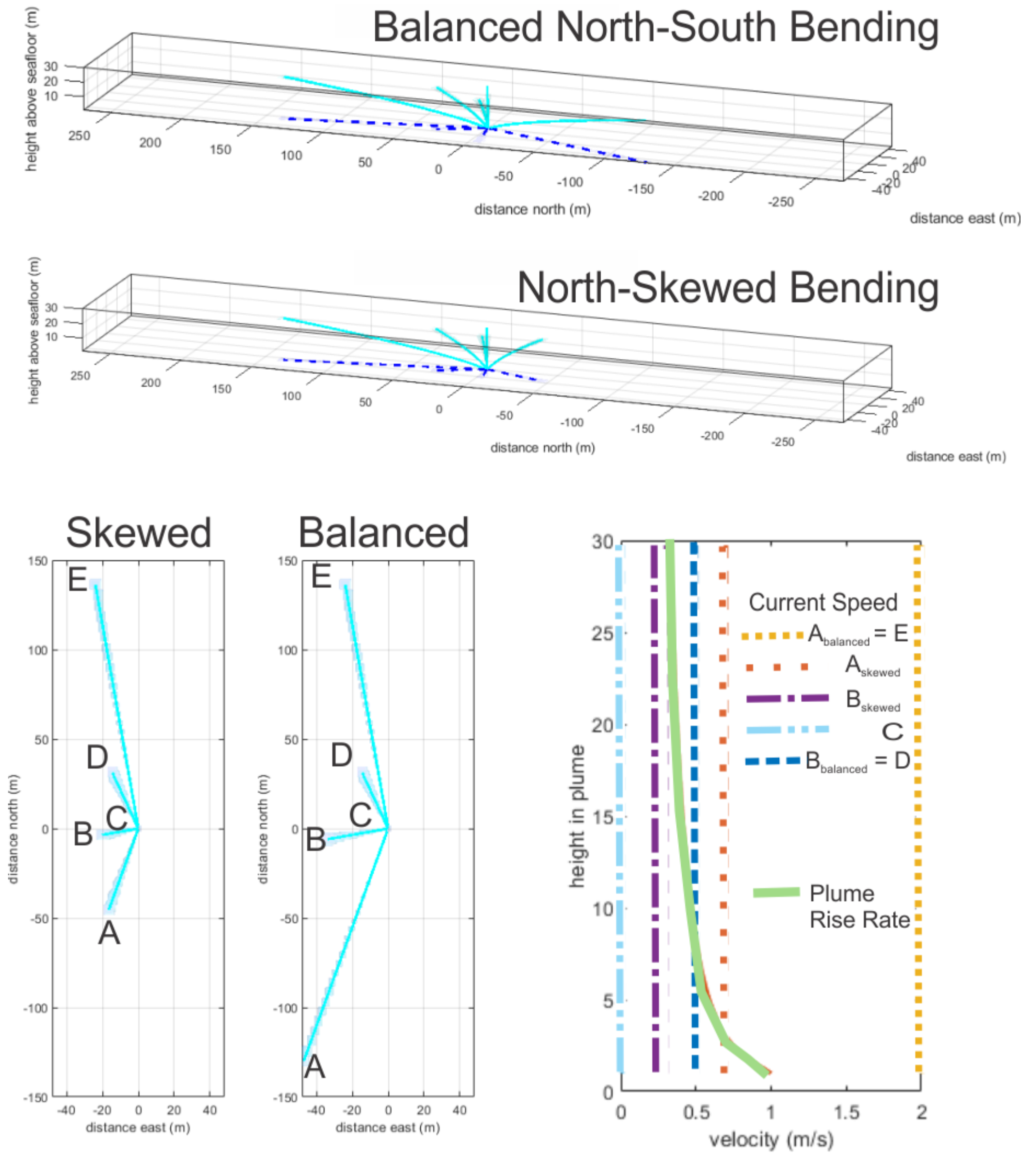
Box 2 – Background on Plumes - continued

Black smokers are where the lithosphere and biosphere are linked through the hydrosphere and are responsible for a large portion of the flux of heat (German and Von Damm,2006) and material (Bickle and Elderfield, 2004) that is transferred from the crust to the ocean. As cold water seeps down through cracks and fissures in the very porous crust, it is warmed by the high geothermal gradient and interaction with the magmatic processes that feed the spreading center (German and Von Damm, 2006 from Bemis et al., 2015). Fluid flow is then focused along faults within the axial valley hydrothermal fields (Kelley et al., 2012) and discharge can either be in the form of high temperature water through chimneys or as lower temperature fluid escaping through mounds, faults and other sea floor cracks. These hot springs are driven by the geothermal energy of the ridge magmatic system (Ondreas et al., 2018) and are a key source for the flux of nutrients and carbon dioxide into the global ocean (Tolstoy 2015, Huybers et al., 2017, Le Voyer et al., 2019,).This superheated fluid becomes rich in dissolved minerals and gasses that convect back to the surface where the dissolved metals precipitate and the dissolved gasses are entrained into the water column as a hydrothermal plume.

As black smoker plumes rise, they interact with the ambient ocean. In particular, their rise speeds and patterns of dispersal are influenced by the oceanographic conditions near the seafloor. The mean near surface currents in the region are characterized by flow to the east and northeast associated with the Eastward North Pacific Current (Strub and James, 2002). However, due to the complex topography associated with the Juan de Fuca Ridge, the background tides and currents of the open ocean are likely modified (Burd and Thompson, 2019). In particular, the interaction of semidiurnal tides with the abrupt ridge topography is expected to generate passive vertical displacements of up to 100 m based on earlier current meter measurements in the area (Mihaly et al. 1998) and on numerical simulations in similar settings (Xu and Lavelle 2017). Low-frequency currents are likely also modified by ridge topography and may result in passive advection of hydrothermal plumes. Significant horizontal excursions (1-2 km in both along and cross ridge directions) may result from energetic counter-clockwise frequency bands in the weather band arising from trapped waves over the ridge (Cannon and Thompson 1996).

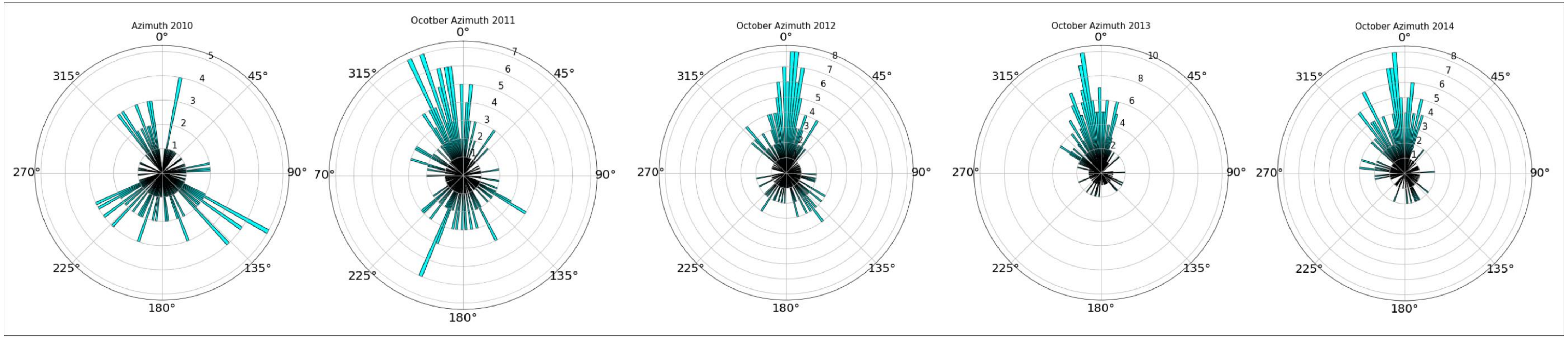
Box 2 – Background on Plumes - continued

The physical behavior of hydrothermal plumes can be quantified by describing the volume, velocity and orientation of the effluent relative to the seafloor (Rona et al., 2006). The geometry and orientation of the plume is the convolved expression of hydrothermal flux from the seafloor and ocean bottom currents in the vicinity of the hydrothermal vent. In a stagnant ocean (no bottom currents), the plumes would rise purely vertically until reaching a level of neutral buoyancy and spreading laterally. But in the presence of ocean tides, the rising plumes are pushed sideways with the direction of offset shifting with the tides. Numerical simulations suggest a non-linear response, but confirm that plume bending directions reflect current/tide directions (Lavelle et al., 2013). The higher the exit velocity of the effluent, the more momentum the fluid has in the vertical direction and thus the less susceptible it is to bending. In addition, the level of lateral spreading, or effective neutral buoyancy, is usually reduced as the ratio of bottom current speed to plume rise rate increases (Lavelle et al 2013, Burd and Thompson 2018, and Adams and Di Lorio 2021). In this study, we characterize the hydrothermal plume associated with the Grotto hydrothermal vent by creating acoustic images of the hydrothermal plumes that are used to measure vertical velocity, volume flux, and heat flux. measure changes in plume direction and bending.



Box 3 – Results: Plume Bending

The primary data of this project is the COVIS Imaging data which gives a 3D reconstruction of the plumes rising above Grotto vent. Slice-by-slice geometric analysis was used to extract the core or centerline of the plume. The azimuth and inclination of the centerline were obtained using a linear fit. We use polar histograms to summarize the mean directions of the azimuths.



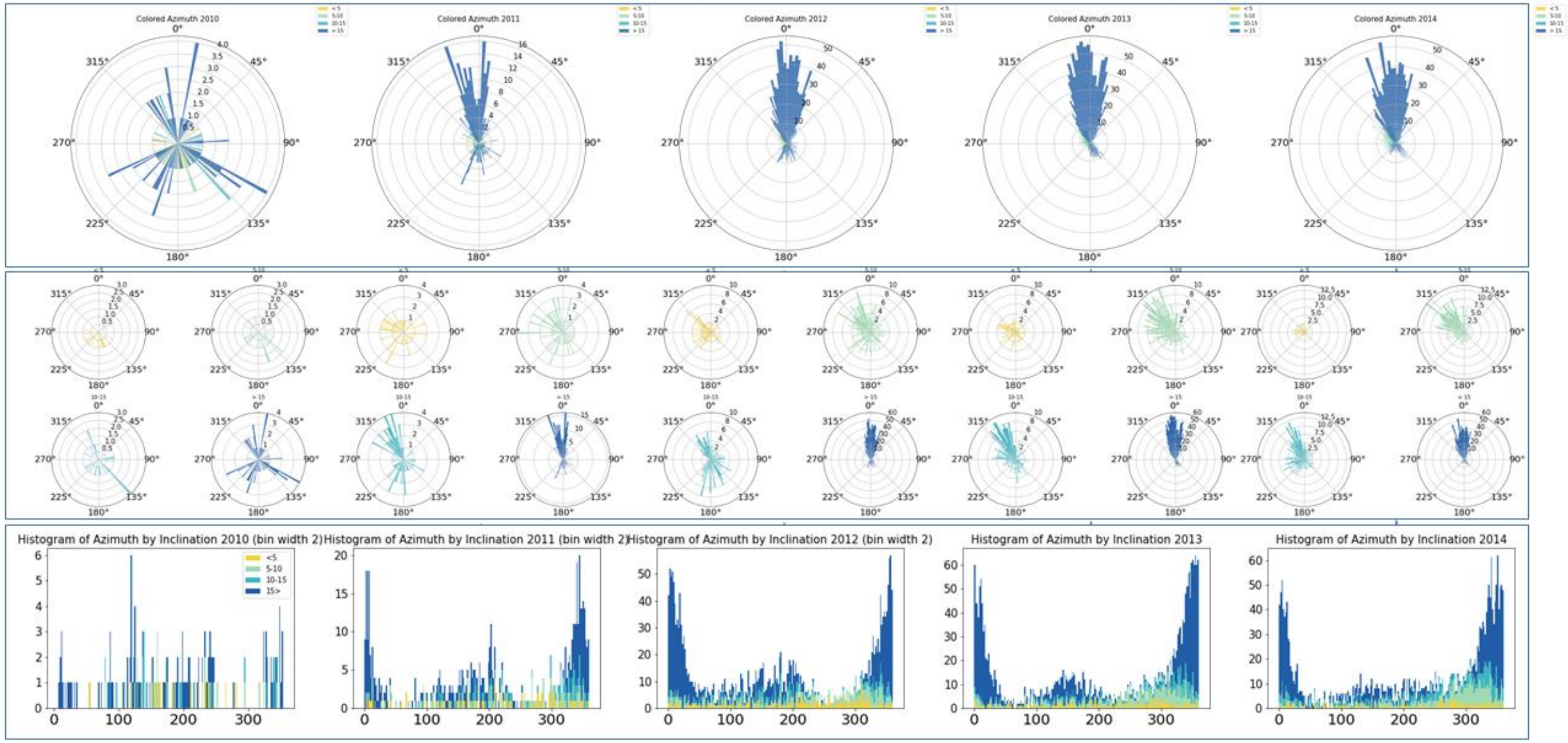
Comparison of plume bending azimuth for the month of October from 2010 to 2014. Each subplot shows a histogram of all plume observations for that year using 2° bin widths and normalizing to the total number of observations in a year. The predominant direction shifts from variable (2010) to northward flow with significant southward flow (2011-2012) to almost entirely northward flow (2013-2014).

Box 3 – Results: Plume Bending - continued

Key Findings

- Looking at a breakdown of azimuths by inclination, the North-South balance of bending appears to be determined by the most bent (inclination>15°) plumes, which tend to be dominantly due north.
- The distribution of inclinations does not vary significantly between years, in part due to the limited spatial extent of the observational data.
- Overall, removing low inclination data from the azimuth distributions has little effect on the primary directions observed, which reflect the directions of strongest bending.

Box 3 – Results: Plume Bending - continued

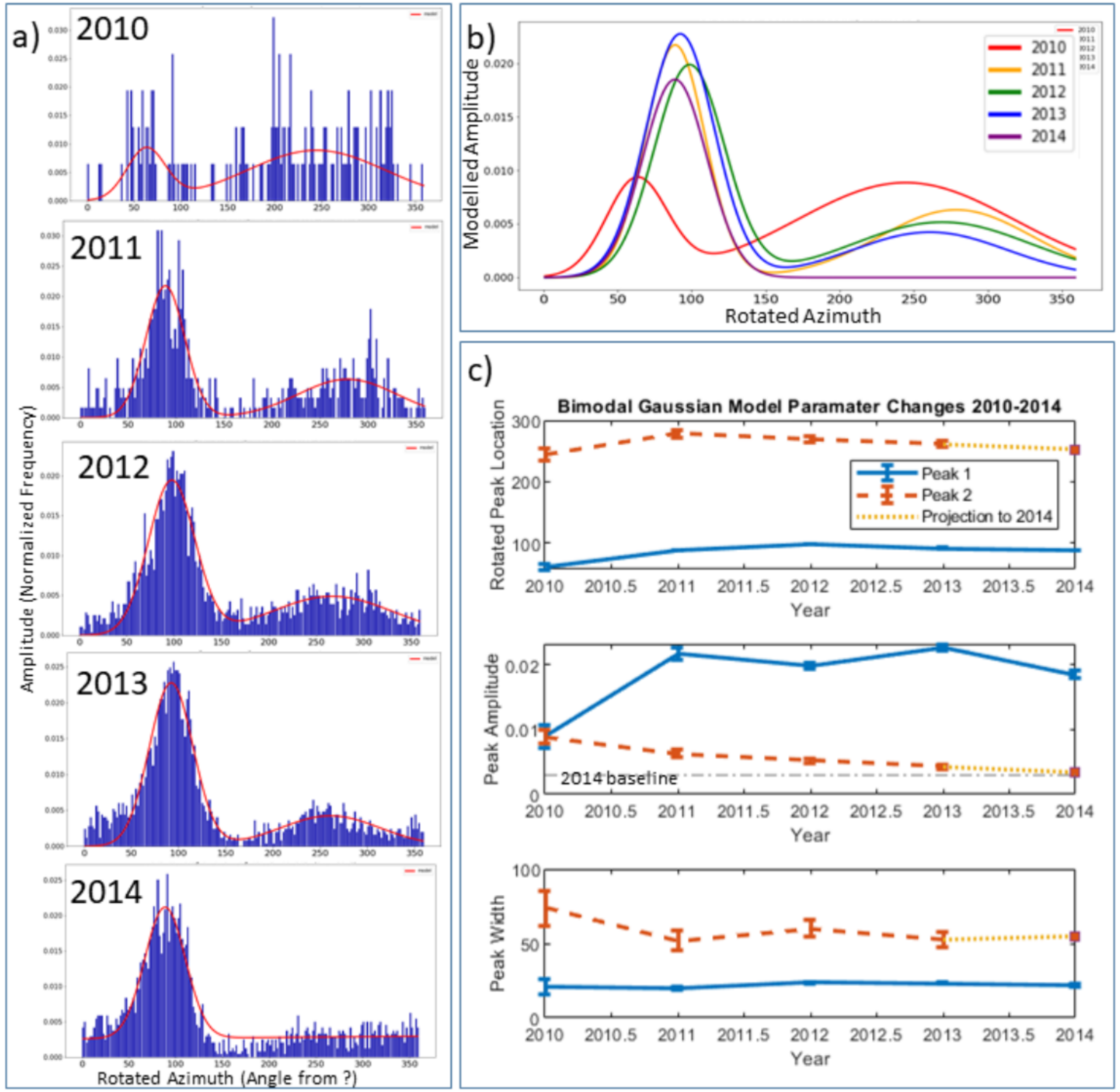


Comparison of plume bending azimuth for the full record in each year. Azimuths are binned separately for inclination ranges of <5° (yellow), 5-10° (green), 10-15° (aqua), and >15° (blue). Separate plots for each range (middle row) confirm that the predominant direction in total histograms (top row) is controlled by the most bent plumes.

Box 3 – Results: Plume Bending - continued

To quantify the above visual analysis we used a non-linear least squares regression. Using curve-fit from the Python scipy package, we modeled the distribution of azimuth data using by first rotating all the distributions by 280° to center the peaks within the distribution range and then fitting a bimodal Gaussian model with error to the azimuthal values. With the exception of 2010, two distinct peaks are found by the fitting routine.

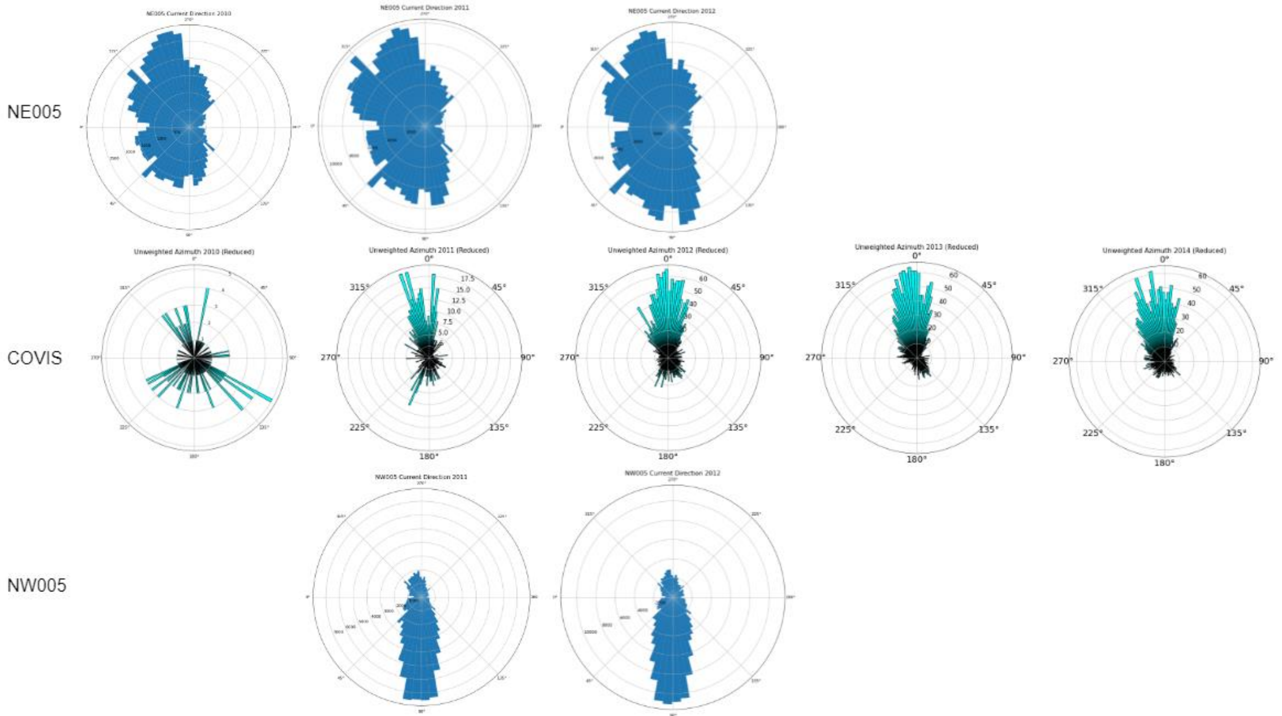
(a) Rotated histograms for plume bending aximuths with model curve showing fit to bimodal Gaussian. The model did not find a second peak in the 2014 data. (b) Combined model curves show the progressive decrease in size of the second peak, suggesting bottom current direction is increasingly influenced by a background mean current that flows northwards (280 degrees off the depicted peak1 direction). (c) Plotting the peak locations (subtract 270°? to get true direction), peak amplitude, and peak widths suggests that the peak bending directions are consistent but the distribution between peak 1 and peak 2 shifts from balanced (equal amplitude) to dominantly peak 1 between 2010 and 2011. Peak 2 amplitude continues to decay into 2014 (when there is no longer any evidence of the secondary peak).



Box 3 – Results: Direct Measurement of Current

Ideally, we would verify our observations suggesting changes in background currents by checking direct bottom current measurements.

- Limited direct measurements of bottom currents exist.
- In particular, four moorings with current meters were planned to bracket MEF, but only one (NE) had viable current data in Oct 2010 to Sept 2011, only two (NE, NW) had data from Sept 2011 to July 2012, and none had data during the remainder of COVIS's deployment.
- The 2010-2013 southward shift of bottom currents at NE005 and the 2010-2013 northward shift of plume bending at MEF/Grotto would both be consistent with an increase in venting at the High Rise site that lies between them.
- It's not clear why the bottom current sat NW005 are different.
- There is insufficient data to directly verify or definitively disprove that bottom current changed.



Annual polar histograms of the current and plume direction for NE005 (top), NW005 (bottom) and COVIS (center panel). From left to right, all valid data for the years 2010 through 2014 are plotted. For each polar histogram, North is at the top and the bin size is 2 degrees.. The NE current meter at 5 m above bottom (NE005) shows a north-south trend in currents consistent throughout 2010-2012 and the NW current meter at 5 m above bottom (NW005) shows a consistently southward current from 2011-2012. In contrast, the COVIS plume data is predominantly of a northward inclination from 2011-2014. Both moorings are about 2 km north of COVIS.

Box 5 - Discussion

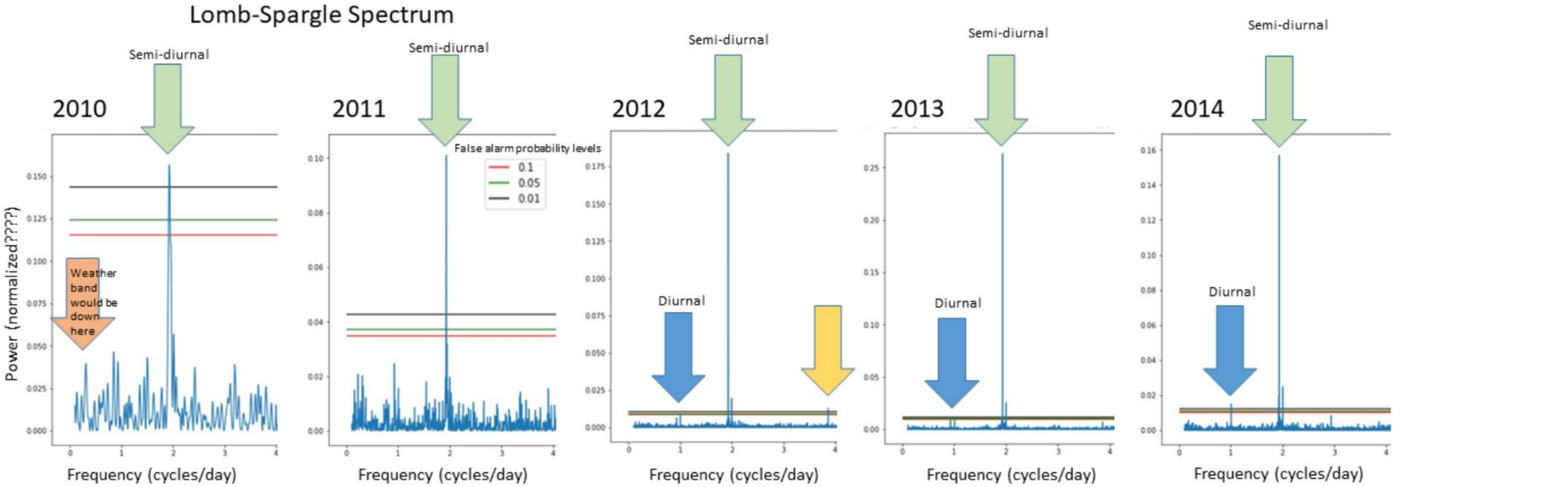
Processes that potentially impact the apparent bottom current direction near Grotto vent and/or more broadly in the Main Endeavor Field include

- Changes in venting intensity at Grotto
- Changes in venting intensity at other vents in the Main Endeavour Field
- Changes in venting intensity at other sites (vent fields) along the Endeavour Ridge
- Changes in the ambient ocean currents due to internal waves generated by any of mesoscale ocean eddy passages, atmospheric storms, or tide-topographic interactions

Few direct measurements of temperature or flow rates exist to verify COVIS estimates of venting intensity at Grotto or to characterize changes in venting intensity at other vents in MEF or elsewhere along Endeavour. Thus we look here at indirect evidence that might support or refute our hypothesis that changing vent intensity in other vents within MEF and in other vent fields along Endeavour are the primary controls on the net background bottom currents. This hypothesis was initially suggest by Thomson et al 2009 based on numerical modeling of the Endeavour hydrography.

Box 5 – Discussion - continued

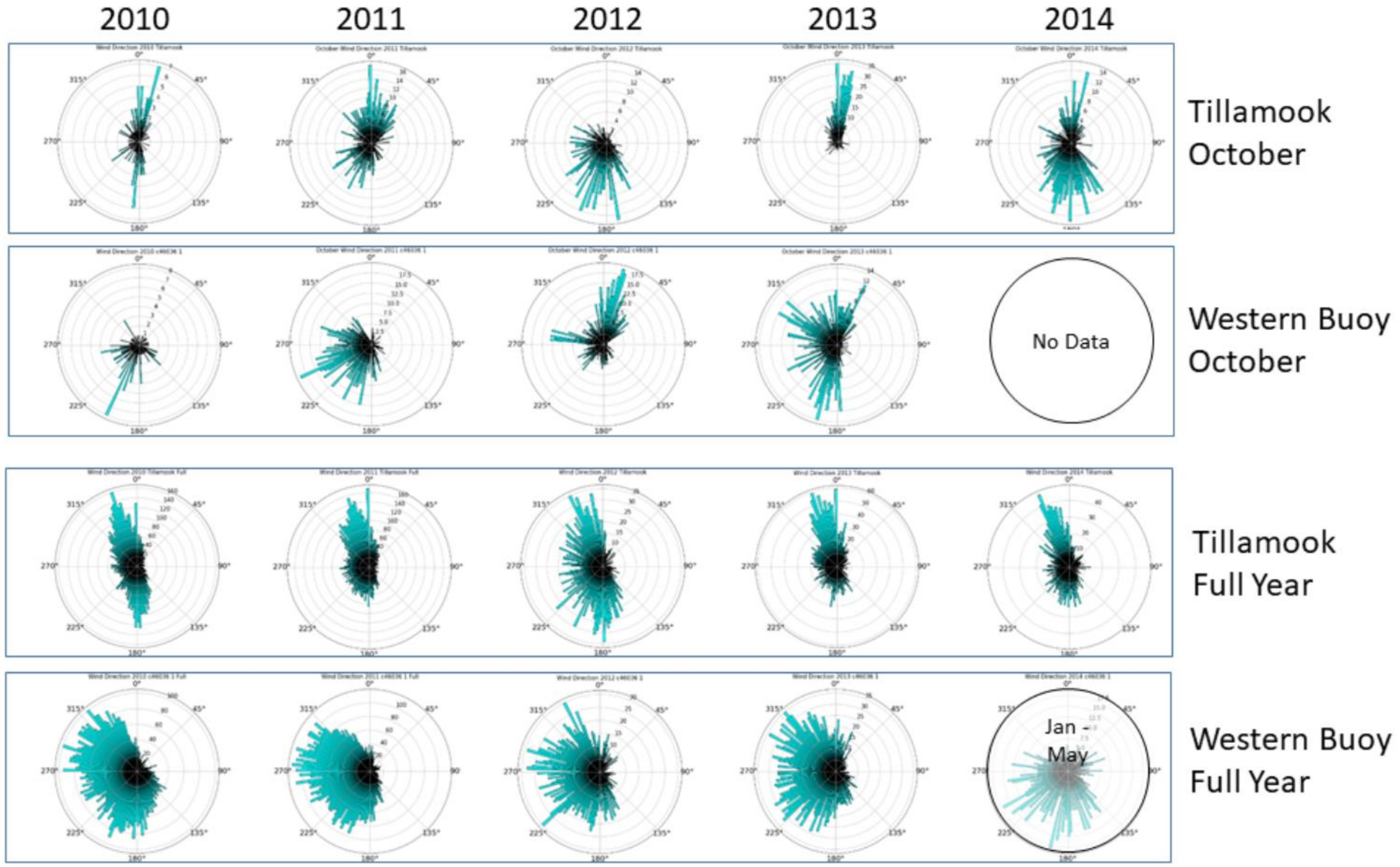
We checked the periodicities in our azimuth data to see whether any of the variability could be attributed to weather or longer than daily tidal patterns. We conclude the only periodicity is the anticipated semi-diurnal tidal cycle typical of Endeavour currents, Nor did we see any significant change in periodicities over the 4 years.



Lomb-scargle spectra for all 5 years show dominant periodicity only in the semi-diurnal cycle (with occasional significant peaks in the diurnal or quarter diurnal ranges). Higher false alarm probability levels in years 2010 and 2011 reflect the shorter duration and more limited data from those years.

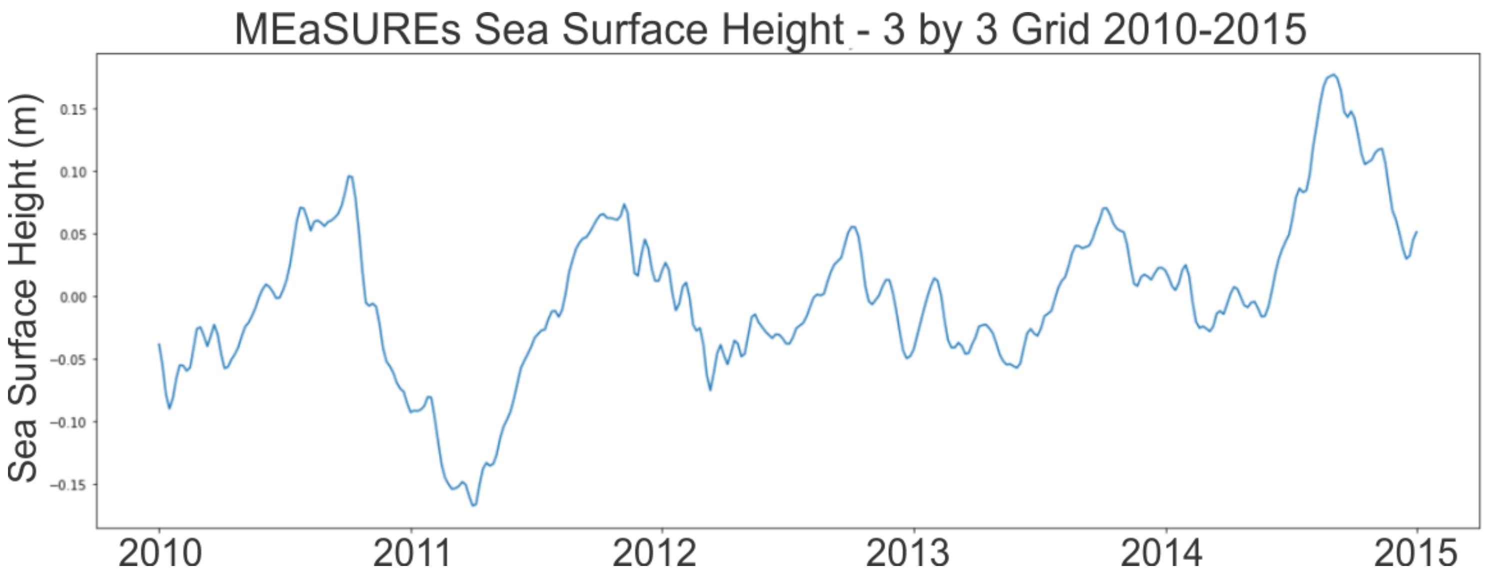
Box 5 – Discussion - continued

We looked at a number of oceanographic and atmospheric factors to check if there were factors outside of Endeavour. Wind data did not show any clear patterns from 2010-2014. Neither did the sea surface height (SSH) data that could have shown changes in the number of mesoscale ocean eddies.



Wind data from eastern coastline buoy (Tillamook) and western open ocean buoy (C46xxxx) suggest that coastal winds varied more than open ocean winds. Neither case shows a simple progressive change in direction from 2010 to 2014.

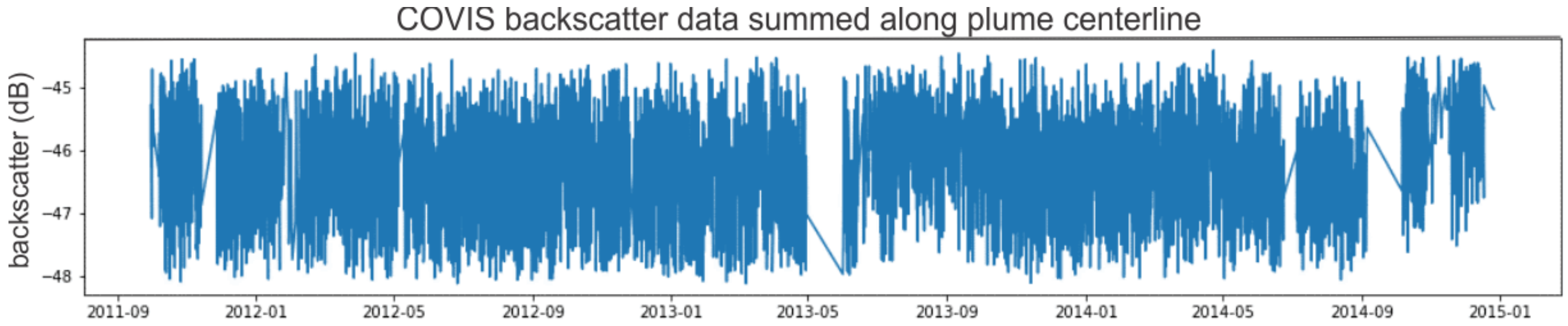
Box 5 – Discussion - continued



Averaged sea surface height averaged over a 56.7 m by 38.1 km large 3 by 3 grid on a 5 day timescale.

Box 5 – Discussion - continued

We also looked more deeply into the Grotto data from COVIS. The Doppler mode data (published in Xu et al 2014) yielded a constant heat flux for Grotto from 2010 to 2014. Here we look at the backscatter data for the imaging data used to obtain the azimuth data as backscatter should reflect the heat content as well. No obvious trend is seen from 2011 to 2014.



Backscattering strength time series from COVIS imaging data. The value varies greatly daily but the mean and range are fairly consistent across the three years depicted.

We conclude that the most likely source of a changing background current is changes in the intensity of venting in the High Rise and MEF vent fields. MEF vents as a whole have been reported as waning since a 2005 earthquake and that may have continued even though Grotto vent itself has not shown significant waning in the 2010-2015 time period. High Rise was reported as waxing during that same time frame.

Plumes entrain ambient fluids as they rise. This results in inward currents with similar scales of speed as peak tidal currents. Thus the combination of stronger venting at High Rise and weaker at MEF would result in a net entrainment current pulling towards High Rise from Endeavour.

Box 6 - Conclusions

- Background bottom currents at Main Endeavour Field shifted between nearly balanced North-South tides in 2010-2011 to a generally northward flow in 2013-2014 based on the changed bending behavior of the Grotto Vent plume.
- Azimuth and inclination of the Grotto plume between October 2011 and December 2014 shifts from bimodal NW and SW to SE in 2010, 2011, and 2012 to single mode NW in 2013 and 2014.
- Spectral analysis of the azimuthal data suggests the dominant current generating processes are either not periodic (such as the entrainment fields generated by the hydrothermal plumes themselves) or are related to tidal processes.
- Thompsen et al 2009 showed in a numerical simulation that the background bottom currents were more likely to be controlled by the local (segment-scale) venting than by outside ocean circulation or atmospheric patterns.

Box 7 - Acknowledgements

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