Aerial infrared imaging reveals large nutrient-rich groundwater inputs to the ocean • Effect of meteor ionization on sporadic-E observed at Jicamarca • Sub-basin scale dust source geomorphology detected using MODIS
Aerial infrared imaging reveals large nutrient-rich groundwater inputs to the ocean

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Regional high-resolution (0.1°C, 0.5 m) low-altitude thermal infrared imagery (TIR) reveals the exact input locations and fine-scale mixing structure of massive, cool groundwaters that discharge into the coastal zone as both diffuse flows and as >30 large point-sourced nutrient-rich plumes along the dry western half of the large volcanic island of Hawaii. These inputs are the sole source of new nutrient delivery to coastal waters in this oligotrophic setting. Water column profiling and nutrient sampling show that the plumes are cold, buoyant, nutrient-rich brackish mixtures of groundwater and seawater. By way of example, we illustrate in detail one of the larger plumes, which discharges ca. 12,000 m³ d⁻¹ (ca. 8,600 m³ d⁻¹ freshwater), rates comparable in volume to high-flux groundwater outputs in better-known tropical karst terrains. We further show how nutrient mixing trends may be integrated into TIR sea surface temperatures to produce surface water nutrient maps of regional extent. Citation: Johnson, A. G., C. R. Glenn, W. C. Burnett, R. N. Peterson, and P. G. Lucey (2008), Aerial infrared imaging reveals large nutrient-rich groundwater inputs to the ocean, Geophys. Res. Lett., 35, L15606, doi:10.1029/2008GL034574.

1. Introduction

Evidence now suggests that while the total freshwater input to the world’s oceans from submarine groundwater discharge (SGD) represents a fraction of that delivered by rivers, the input of nutrients to coastal environments via SGD is disproportionately large due to its elevated nutrient load [Burnett et al., 2006]. Groundwaters typically bear high concentrations of dissolved chemical components, including biolimiting species of N and P, making SGD a particularly important pathway in coastal ocean biogeochemical and ecological systems [Miller and Ullman, 2004; Slomp and Van Cappellen, 2004]. The discharge of nutrient-rich groundwater to coastal waters has been a key factor for causing disordered growths of marine phytoplankton and macroalgae, which have consequently lead to changes in aquatic habitats and species compositions [Valiela et al., 1990; Paerl, 1997], effects which may produce a cascade of changes throughout associated ecosys-tems [Bowen et al., 2007]. In several regions, large-scale harmful algal blooms have, in part, been directly linked to groundwater-borne nutrients. [Larouche et al., 1997; Hu et al., 2006; Y.-W. Lee and G. Kim, 2007]. In areas with contaminated aquifers, groundwater is also a potential source of pollutants and bacteria to the ocean [Boehm et al., 2004]. Thus, as human populations continue to develop within an aquifer’s reach of the coastal zone, the impact of groundwater-borne nutrients and other dissolved species to the nearshore ocean will simultaneously expand. In regions where stream flow is limited, subterranean inputs become an especially important component of linkages between land and sea.

The recognition that SGD is an important pathway for nutrients, contaminants, and other components requires that we develop the necessary tools to up-scale assessments to regional bases. While progress has been made, it remains difficult to evaluate and resolve spatial variations in subterranean discharges over scales of more than a few kilometers. Recognizing this need, we initiated a study to evaluate the use of aerial thermal infrared (TIR) imagery to quantify SGD. We selected the dry, western side of the island of Hawaii as a prime study area since SGD from large islands appears to be volumetrically more important than that found from continents [Zektser, 2000; Kim et al., 2003; J.-M. Lee and G. Kim, 2007], and because the groundwater at this site is the only significant source of freshwater to the coastal ocean [Oki et al., 1999].

The aerial TIR surveying method is applicable wherever there are temperature and density differences between coastal marine waters and discharging terrestrial groundwater. It has been locally utilized at high latitudes where groundwaters are warm relative to seawater [Roxburgh, 1985; Banks et al., 1996; Miller and Ullman, 2004], and at lower latitudes where groundwaters are cool [Shaban et al., 2005; Duarte et al., 2006]. Average groundwater temperatures in coastal aquifers along Hawaii’s west coast (∼20°C) contrast with ambient coastal ocean temperatures (typically 24–28°C), making temperature an important SGD tracer. Because the groundwater is less saline than coastal seawater, it forms buoyant cool water “plumes” and more diffuse discharges that can be mapped and quantified using aerial sea surface thermal imaging. Cold water anomalies along the shoreline due to vertical mixing perturbations appear minor in our study region since cold water seeps are coincident with groundwater tracers (radon, salinity, nutrients).

We surveyed surface water temperatures along west Hawaii using an airborne spectrometer with an accuracy of ~0.5°C and a spatial resolution of 0.5 m. This high-resolution TIR imagery captured detailed temperature variations within and spatial extents of groundwater flowing...
into and mixing with the ocean in exquisite detail. With it, we identified 31 point-source groundwater discharge plumes with a surface area extent >13,000 m² (Figure 1) along ~100 km of coastline and have conducted detailed ground-based measurements and flux rate studies on seven of these. In this paper, we illustrate the aerial TIR character, surface water nutrient chemistry, water column structure, and measured discharge rates of these plumes, using the groundwater outflow from a small boat harbor as an example of the utility of our approach and significance of our findings.

2. Methods

2.1. Aerial TIR Surveys

Initial TIR surveys were conducted in August 2005 over Kaloko-Honokohau National Historical Park and Kealakekua Bay areas. Subsequent TIR mapping in May 2007 surveyed the entire region depicted in the Figure 1 inset. Surveys were conducted at 1,100 m altitude using a TIR spectrometer (sensitivity of 0.1°C) mounted in an aircraft’s fuselage that produced TIR images for each flight line. After the aerial surveys, each flight line image was spectrally calibrated to onboard blackbody measurements made between each flight line. All bands between 8.1 and 11.0 μm in the calibrated line images were then averaged to single band and subsequently converted to temperature by inverting the Planck equation [Pieters and Englert, 1993]. The temperature-converted images were georeferenced using the aircraft’s navigational parameters, referenced to regional aerial photographs using tie points, and then mosaicked to form high-resolution surface water temperature maps. The temperatures in the mosaicked images were then calibrated to twelve in situ thermistors (Onset HOBO). This process removes atmospheric interferences (e.g. water vapor and aerosols) between the ocean’s surface and the airborne sensor. (Full details of surveys in auxiliary material).

2.2. Temperature and Salinity Profiles and Nutrients

Vertical water column profiles of temperature and salinity were measured at SGD sites within several hours of low tide in order to coincide with maximum groundwater discharge. In situ temperature/salinity measurements were made with a YSI probe accurate to ±0.15°C and ±1% salinity. Water samples were collected between August 2005 and May 2007 throughout west Hawaii to determine regional nutrient characteristics. Samples were collected in pristine freshwater wells, brackish wells and ponds along the coastline, and nearshore and offshore ocean surface (upper 0.15 m) waters. Samples were filtered (0.45-μm GF/C) and analyzed at the University of Washington using spectrophotometric segmented flow nutrient analysis. Respective standard errors (n = 10) for Si(OH)₄, NO₃, and PO₄³⁻ were 1.1%, 2.5%, and 3.4% of measured concentration.

2.3. Groundwater Discharge Fluxes

Groundwater discharge fluxes were estimated using two natural groundwater tracers, ²²²Rn (enriched in groundwater) and salinity (depleted in groundwater), which were continuously measured at discharge locations for several tidal cycles. Inventories of ²²²Rn and salinity were used in a non-steady-state mass balance model that accounts for their inputs and outputs at discharge sites, in which the tidal and SGD water fluxes are the unknown factors. Coincident mass balance equations for ²²²Rn, salinity, and tidal water volumes were solved [Peterson et al., 2007] to calculate both freshwater and total (freshwater + recirculated seawater) groundwater discharge. Our procedures and calculations are detailed in the auxiliary material.

3. Results and Discussion

Our TIR imagery indicates that SGD for the surveyed region occurs as more than 50 point-source discharges (distinct SGD portals at the shoreline) and ~12 diffuse discharges (seepage disseminating from more extensive segments of coastline), both of which primarily occur in embayments. This is expected as groundwater table heights follow surface topography, and subsurface flow is hydraulically directed towards sea level. Thus, groundwater flow lines are directed toward and converge at coastal embayments. As those embayments are naturally or artificially enlarged, they proportionally intersect larger areas of the groundwater table and discharge larger volumes of SGD flow.

At Honokohau Harbor, as elsewhere along the coast, temperature-salinity profiles show that its cool seaward-flowing brackish surface plume is less than a few meters thick and overrides warmer and denser seawater that flows landward beneath it (Figure 2). As the brackish water surface plume flows seaward, it mixes with and entrains the warm incoming seawater below [Bienfang, 1980]. Propellers from boats moving through the plume pull warm water up into the cool, brackish surface water lens (Figure 1). Combining ground-based measurements from several areas along the west coast of Hawaii, we determined that a statistically robust linear correlation exists between temperature and salinity in marine waters throughout the region (Figure 3a).

Based on mass balances of ²²²Rn, salinity, and water fluxes for Honokohau Harbor (details in auxiliary material), we estimate the total groundwater flux to be 12,000 m³ d⁻¹, with an average salinity of 15.2 and a ²²²Rn activity of 25,500 dpm/m³. The corresponding flux for the terrestrial freshwater component of this discharge is 8,600 m³ d⁻¹, based on a salinity of 0 and a ²²²Rn activity of 39,100 dpm/m³. Compared to the freshwater output of massive artesian springs in tropical karst, both our modeled total SGD and freshwater fluxes are moderately large in terms of flow rate, being classified [Rosenau et al., 1977] as Magnitude-3 Springs (~2,400 to ~24,000 m³ d⁻¹). For arid west Hawaii, however, these water and associated nutrient fluxes are substantial. Calculated on a basis of unit width of shoreline, our estimated freshwater flow from the harbor’s 80-m wide mouth is equivalent to ~107,000 m³ d⁻¹ km⁻¹. A regional water budget [Kay et al., 1977] estimated an average freshwater discharge of ~15,000 m³ d⁻¹ km⁻¹ for a ~26-km length of shoreline north of our study area. More locally, using a numerical groundwater flow model developed for the regional aquifer in west Hawaii, Oki et al. [1999] calculated a freshwater coastal discharge within
adjacent Kaloko-Honokohau National Historical Park of \( \sim 7,000 \text{ m}^3 \text{ d}^{-1} \text{ km}^{-1} \). These comparisons show that the point-source freshwater outputs documented by our TIR mapping are focused and amplified several times over background non-point-source regional SGD.

Regional SGD nutrient characteristics are illustrated by plots of silica, nitrate, and phosphate concentrations relative to salinity (Figures 3b–3d). Linear regressions of these data for ocean surface waters of the region (salinities 7–35) show clear linear seaward decreases of all nutrients with increasing salinity, indicating conservative mixing and dilution with ambient seawater (the one exception being anthropogenic inputs of phosphate to Honokohau Harbor; see auxiliary material). These linear trends show no net apparent biological nutrient draw-down in ocean surface waters, despite substantial nutrient loading from SGD (a phenomena previously observed by Dollar and Atkinson [1992]), although our regional observations of nutrient loading and seaward mixing do not preclude biological utilization. If there is biological uptake of these nutrients (as one might expect), it is masked by the very high rates of nutrient supply.

Figure 1. Sea surface temperature (SST) map produced from August 2005 aerial TIR survey over coastal waters in the vicinity of Kaloko-Honokohau National Historical Park, located on the west coast of the Island of Hawai‘i. The SST image is a temperature-corrected, georectified mosaic of 135-m wide swath images with a spatial resolution of 0.5 m. White triangles in the inset indicate the positions of 31 major (surface area >13,000 m²) point-sourced SGD plumes identified by TIR imagery. See text for discussion of integrating surface water nutrient concentrations into the TIR image.
With the possible exception of phosphate, Y-intercepts of the nutrient mixing trends fail to intersect the zero-salinity nutrient concentrations measured in pristine freshwater aquifers (Figure 3). Although brackish coastal ponds and coastal well waters are spatially located between the marine SGD nutrient plumes and pristine high-elevation freshwater aquifers, they show significant deviation from the well-defined ocean mixing trends. Nitrate in coastal wells, in particular, shows marked enrichments relative to both the marine mixing regression and the freshwater aquifers. Natural leaching from the variety of west Hawaiian soils with differing plant covers [cf. Vitousek, 2004], and local anthropogenic contributions from fertilizers and septic systems likely all contribute to these variations. Moreover, the coastal (anchialine) ponds are small, shallow, and often support a unique assemblage of invertebrate and algal species [Maciolek and Brock, 1974], and thus internally modify their own micro-environmental chemistry. All these deviations illustrate that the nutrient compositions of the Hawaiian groundwaters undergo modification during their transit from inland recharge areas toward coastline exit portals, a phenomena well documented in many groundwater systems [Slomp and Van Cappellen, 2004; Bowen et al., 2007; Santos et al., 2008]. However, despite all these modifications, what is most important with regards to nutrient dynamics in west Hawaii is that the region’s aquifers are naturally enriched in Si-N-P, and that

Figure 2. Water column temperature (a) and salinity (b) profiles for Honokohau Harbor, August 2006. Location and depth of individual measurements are shown by black dots. The relatively cool, brackish, nutrient-rich plume flows seaward above warm, dense seawater flowing landward [Bienfang, 1980]. Data tables included in auxiliary material.

Figure 3. (a) In-situ measurements (cross symbols) from transects in Honokohau Harbor and Kealakekua Bay (Figure 1 inset) indicate a strong linear correlation between temperature (T) and salinity (S) for coastal ocean waters in the west Hawaii region. Open diamonds represent temperature and salinity measurements in the upper 0.5 m of the Honokohau Harbor plume. (b–d) Dissolved silica, nitrate, and phosphate concentrations in pristine freshwater wells (open squares), brackish wells (open triangles), brackish ponds (open circles), and ocean surface waters (open and closed diamonds) from samples collected in Honokohau Harbor, Kealakekua Bay and Kailua Bay. Linear regressions are for ocean samples only; phosphate regression excludes Honokohau Harbor (open diamonds). Data tables included in auxiliary material.
discharge of groundwater into the ocean must be the only source of new nutrients to the oligotrophic waters of the region.

[14] TIR mapping can provide a framework for integration of a variety of ancillary data sets, so long as those data are coherently related to temperature. The relatively constant temperature, salinity and nutrient trends in the marine surface waters of west Hawaii, for example, allow our TIR imagery to be used as an approximation of surface water nutrient distributions. This can be accomplished by combining linear temperature-salinity variations with linear nutrient-salinity trends. Since we lack a statistically robust temperature-salinity data set solely for the period of the initial TIR flight (August 2005), we take advantage of persistent temperature-salinity relationships within the Honokohau Harbor plume (Figure 3a), which are dominated by the high rates of SGD inflow and are sheltered from inter-seasonal open ocean temperature extremes. Solving this localized linear temperature-salinity correlation for salinity (Figure 3a), and substituting the resulting function into each regional nutrient-salinity trend (Figures 3b–3d) yields co-linear correlations relating nutrient concentrations to surface water temperature. The resultant in situ nutrient-to-TIR temperature integrations are illustrated in the boxed inset of Figure 1. We caution that such up-scaling integrations depend on critical consideration of the variables involved, including nutrient drawdown by biota, coastal ocean mixing dynamics, anthropogenic nutrients, and localized runoff effects on temperature, salinity and nutrients.

4. Conclusions

[15] This work demonstrates that aerial infrared surveying is an efficient method for mapping SGD on a large-scale basis and, when combined with ground-based studies, forms a powerful tool for regional SGD analysis. High-resolution aerial imagery along west Hawaii details inputs and seaward mixing of cool, brackish, nutrient-rich groundwaters discharging as both point-source plumes and diffuse flow. On west Hawaii, these nutrient inputs represent the sole source of new nutrient delivery to the coastal ocean. Estimates indicate point-source discharges are amplified over background SGD and are comparable in magnitude to large springs in continental coastal regions. High groundwater fluxes and rapid oceanic mixing produce conservative temperature, salinity, and nutrient relationships, allowing SST to be used as a semi-quantitative estimate of spatial sea-surface nutrient concentrations in this region. Most importantly, however, is the principal strength of TIR surveying in the coastal ocean, which is the ability to differentiate and map inputs of water masses with differing SST, and up-scaling quantitative discharge estimates. The TIR technique for recognizing SGD is not limited to tropical regions, but can be applied in a variety of other environments wherever temperature contrasts exist, such as where stream flow to the ocean has a different temperature than groundwater, or in temperate latitudes where warm groundwaters intrude colder seawater.

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References

Slomp, C. P., and P. Van Cappellen (2004), Nutrient inputs to the coastal ocean through submarine groundwater discharge: controls and potential impact, *J. Hydrol.*, 295, 64–86.


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