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Intonation of Greek in contact with Turkish: a diachronic study

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Abstract
Asia Minor Greek (AMG) speakers cohabited with Turkish speakers for eight hundred years until the 1923 Lausanne Convention, which forced a two-way mass population exchange between Turkey and Greece and severed their everyday contact. We compare the intonation of the continuation rise tune in the speech of first-generation AMG speakers born in Turkey with three subsequent generations born in Greece. We examine how long contact effects in intonation persist after contact has ceased, through comparison of the f_0 patterns in four generations of AMG speakers with those of their Athenian Greek- and Turkish-speaking contemporaries. The speech of the first-generation of AMG speakers exhibits two patterns in the f_0 curve shape and time alignment of the continuation rises, one Athenian-like and one Turkish-like. Over subsequent generations use of the latter diminishes, while the Athenian pattern becomes more frequent, indicating intergenerational change.

Keywords: intonation; continuation rise tune; diachronic data; curve fitting; intergenerational change

Prosody in Contact

Prosodic aspects of language contact are understudied, even though insights from such research are required to deepen our understanding of resultant language change. There is increasing evidence that *ongoing* language contact results in intonational variation and change in the speech of bilingual speakers in different ways.

Contact between languages may result in either phonological or phonetic prosodic transfer (Mennen, 2006), influencing the category of phonological tonal events (pitch accents and edge tones) or their phonetic realization. For example, in Buenos Aires Spanish, which was in long-term contact with Italian, prenuclear accents in broad focus declaratives display the Italian early-peak H tone alignment at the beginning/middle of the stressed vowel, rather than the Spanish late-peak alignment in the stressed or the following syllable (Colantoni & Gurlekian, 2004). Similarly, in Peru, Lima Spanish speakers who do not have contact with Quechua produce earlier peak alignment in contrastive rather than in broad focus (a pattern found in

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Peninsular Spanish) while Cuzco speakers who are Spanish-Quechua bilinguals do not consistently differentiate between broad and contrastive focus, something that is attributed to the influence of Quechua (O'Rourke, 2012).

Sometimes contact gives rise to novel patterns attested in neither language. Lekeitio Spanish, a contact variety of Basque and Spanish, displays mixed properties of Basque and Spanish intonation, that is, accents in broad focus declaratives are not falls, as in the H*+L of Lekeitio Basque, but rises as in the L*+H or L+H* of Madrid Spanish. On the other hand, the peak alignment of the H tone in the L*+H rises does not appear after the stressed vowel as in Spanish but within the stressed vowel, as in Lekeitio Basque (Elordieta & Calleja, 2005).

In addition, bilingual speakers have been shown to codeswitch in prosody. Queen (2012) reported codeswitched productions in the polar question tunes of German-Turkish bilinguals: when the Turkish question particle /-mI/ was inserted into a German matrix utterance, the question particle was produced with a falling (H*L) Turkish f_0 contour.

Evidence is still lacking on whether and how long such effects persist after contact has ceased, as few studies exist on the *diachronic* change of intonation (Hualde, 2004). Colantoni and Gurlekian (2004) argue that the alignment patterns still found in Buenos Aires Spanish declaratives almost sixty years after the end of the immigration wave of Italians are due to the covert prestige of Italian. Barnes and Michnowicz (2015) report that the contact between Veneto Italian and Mexican Spanish in Chipilo, Mexico resulted in Italian-like patterns of prenuclear peak alignment in broad focus declaratives. They maintain that the influence of Veneto Italian has persisted because speakers identify with Veneto and are proud of their language and heritage.

Similarly lasting effects of contact have been documented in the direction from a dominant to a nondominant language. Bullock (2009) discusses prosodic patterns in French-English contact in a minority variety of French spoken in Frenchville, Pennsylvania since the 1830s. In the last two remaining fluent heritage speakers in the village, there was adoption of additional structures of the dominant language (i.e., pitch accents used in English but not in French) in the intonation of these French heritage speakers, which have distinct pragmatic uses.

In this paper, we trace the trajectory of intergenerational prosodic change in *four* generations of speakers of Asia Minor Greek (AMG). AMG patterns are compared with those of four generations of their Turkish-speaking contemporaries to bring to light any similarities that may have remained after the end of AMG-Turkish contact and four contemporaneous generations of Athenian speakers, since AMG speakers have now been living in Greece for almost a century (see Baltazani, Przedlacka, & Coleman, 2020).

Our approach differs from those cited above in several respects. First, we make a three-way comparison analyzing benchmark data from Athenian and Turkish in addition to AMG, whereas the papers cited above (with the exception of Baltazani et al., 2020) only analyze data in the contact variety, relying on previously published analyses of the two source languages. Second, we investigate data from four generations, whereas most of the papers cited above use data from just one or two. Third, whereas most studies use small corpora of speech elicited in a laboratory setting, we

employ a large corpus of mostly spontaneous and semispontaneous speech because of the stronger influence of the source language on a contact variety in natural than in controlled laboratory speech (Barnes & Michnowicz, 2015).

Background on Athenian, Turkish, and AMG

Athenian, the Modern Greek variety spoken in Athens, is the standard used for official purposes, in education, and the media. Athenian is thought not to be distinctly marked by any single traditional Greek dialect (Trudgill, 2003:48). Rather, extensive internal migration from various rural parts of the country to Athens between 1950 and 1980 resulted in today's amalgamation[1] of different varieties brought by migrants (Allen, 1986).

Despite reports on the leveling influence on Turkish of the Istanbul standard used in mass media and the education system since the 1930s (Johanson, 2001:16), there are descriptions of phonological, morphological, and syntactic dialectal features for several regions in Turkey, including the Black Sea (Johanson, 2001), Marmara, Aegean, and Central Anatolia regions (Karlık & Akbarov, 2015). To our knowledge, no descriptions exist about dialectal intonation differences. As we base the analysis of Turkish patterns on recordings from several geographic regions, we conducted a statistical comparison of the intonational parameters in these dialectal recordings (in 3.1), which revealed that they are similar, so for all subsequent analyses we grouped all Turkish data together.

AMG is a variety of Modern Greek previously spoken in Asia Minor by people whose ancestors had been part of the Byzantine Empire until the eleventh century conquest by Seljuk Turks. (For a detailed, well-documented linguistic history, see Karatsareas [2011:11-63] and sources cited there.) The Greek-speaking peoples in Asia Minor mixed culturally and linguistically with Turks for eight centuries in a society where Turkish was the dominant language. There is historical evidence of some linguistically Turkicized Greek communities and of others retaining Greek as their first language (Karatsareas, 2011:16-19). In 1923, the cohabitation was forcibly ended due to the Convention Concerning the Exchange of Greek and Turkish Populations. Approximately 1,300,000 Orthodox Christians of the Ottoman Empire were relocated to Greece, in exchange for roughly 360,000 Muslims from Greece to Turkey (Blanchard, 1925).

AMG is a heritage variety (Polinsky, 2018) only spoken at home and not dominant at the national level. It survives mostly in northern Greece (Katsapis, 2011:71) where currently there are second-, third-, and fourth-generation speakers of AMG who, unlike the first generation, did not grow up in a Turkish-speaking environment. The speakers are bi- or tridialectal, in AMG, local varieties, and Athenian Greek as part of their linguistic repertoire (Janse, 2009; Karatsareas, 2011). First-generation speakers in this study were born in Cappadocia prior to the 1923 Convention while speakers of subsequent generations are descendants of the Cappadocian refugees and were born in Greece. Refugees from Asia Minor made up more than a quarter of Greece's population in the 1928 census (Katsapis, 2011:126-29) and were viewed by many as an economic burden. The already ailing economy and the politically unstable system at the time resulted in the marginalization of these refugees (Gizeli, 1984), negative attitudes toward them (Kalafati, 2018), and stigmatization of their language.

Materials and methods

Data, speakers, and annotation

We depart from the controlled laboratory methodology followed in most Autosegmental-Metrical studies of intonation (Ladd, 2008) and instead draw on natural speech corpora, because many of the sociolinguistic parameters affecting the behavior of bilingual speakers are not well understood and cannot be replicated in the laboratory. We extracted 2,977 continuation rise utterances from 111 speakers (seventy-one male, forty female) varying in length, complexity, lexical makeup, syntactic structure, and style from the sources listed in Appendix A. Table 1 presents the number of tokens and speakers analyzed per language variety and generation.

AMG speakers here were divided into four generations based on date of birth and historical circumstances. For consistency with the generational categorization in one of the AMG corpora we used (Janse, 2015), we classified speakers born in Turkey before 1923 and their Turkish and Athenian contemporaries as Generation 1. Subsequent generations were divided as follows: second-generation speakers born between 1923 and 1945 (the oldest was in fact born in 1927), third-generation from 1950 to 1975, and fourth-generation after 1978.[2] The oldest speaker in the recordings across all three varieties was born in 1879, the youngest in 1994, their birthdates spanning over a century.

The first-generation AMG speech was drawn from archival as well as contemporary field recordings, thus some members of this generation were recorded in their youth, others in their old age. For this generation, the shape of the modeled f_0 curves and the location of peaks and troughs in continuation rise tunes in archival recordings were compared to those in contemporary recordings (see *Statistical analysis* section and Baltazani et al., [2020] for details of this method). This comparison revealed no significant differences in f_0 shape or in the location of peaks and troughs due to recording date (Baltazani et al., 2020), so all the data on first-generation AMG speakers regardless of the recording date are pooled together in the subsequent analysis.

We defined continuation rises in all three varieties as phrases marked with an H tone on their right boundary (in Autosegmental–Metrical terms, H− or H%), indicating that the speaker has not finished speaking (see Analysis of f_0 contours section for details). In the Athenian continuation rise tune there is typically an L* nuclear pitch accent (i.e., an f_0 trough) aligned with the stressed vowel of the nuclear word, followed by an H− phrase-final accent (i.e., the phrase ends in high f_0; Arvaniti & Baltazani, 2005; Baltazani & Jun, 1999; Figure 1 top). In the Turkish continuation rise tune a H*+L nuclear pitch accent (i.e., an f_0 peak plus a fall) is followed by a H− phrase accent (Ipek & Jun, 2014; Özge & Bozsahin, 2010; Figure 1 bottom). The f_0 movement is a simple rise in Athenian but a rise-fall-rise in Turkish.

Planned comparisons

For all comparisons, we examined the modeled f_0 curves to find differences in their shape, including location of peaks and troughs (see Analysis of f_0 contours section for

Table 1. Number of tokens and speakers per language variety and generation

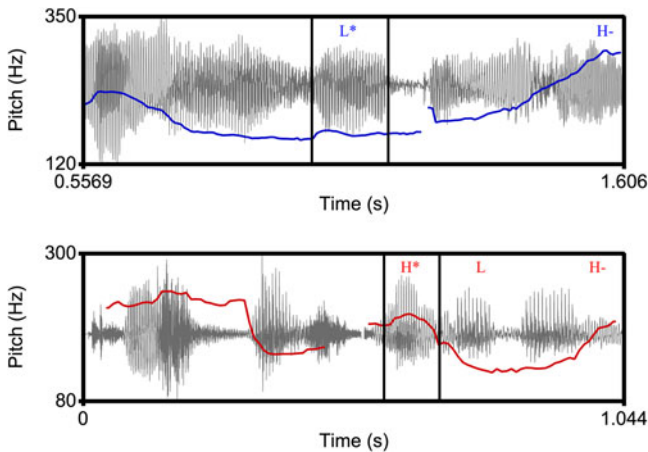| Generations		Athenian	AMG	Turkish
Generation 1	Tokens	255	355	470
	Speakers	8M, 8F	5M, 3F	17M, 5F
Generation 2	Tokens	210	396	98
	Speakers	7M, 6F	4M, 3F	6M, 3F
Generation 3	Tokens	272	333	95
	Speakers	2M, 1F	5M, 1F	7M, 4F
Generation 4	Tokens	101	281	111
	Speakers	2F	7M, 1F	3M, 3F
Total	Tokens	838	1365	774
	Speakers	17M, 17F	21M, 8F	33M, 15F

Figure 1. Representative examples of continuation rise tunes in Athenian (top) [erɣa'zotane] " (she was) working" and Turkish (bottom) [ma'saja o'**tur**madan] "Before sitting at the table." The rectangles near the center of each figure indicate the nuclear vowel, transcribed in bold.

details). Two sets of comparisons were conducted: (1) *Geographical region comparison* (for Turkish only). The Turkish recordings were from several regions, including Istanbul, the Black Sea, the Aegean, and Central Anatolia. (Recordings from the Doegen corpus of Turkish speakers from the territory of the Ottoman Empire in what is now Romania are included as a fifth sample in order to examine whether or not this data is similar to the other varieties); and (2) *Diachronic comparison*. This was a comparison across the three varieties and four generations to determine the similarities of AMG to Turkish and Athenian, and whether or how their intonation may have changed over the generations.

Analysis of f_0 contours

Our quantitative analysis of the shape and relative timing of f_0 contours of continuation rises involves the following steps:

1. Standardization of audio file formats.
2. Identification of utterances containing continuation rises.
3. Estimation of f_0 contours, quality control, and elimination of f_0 tracking errors. This step includes transformation of f_0 to semitones above or below the utterance mean.
4. Functional Data Analysis I: Modeling the f_0 contours of whole utterances, using tenth order polynomials, in order to precisely determine the timing of the trough that is used to compare alignment between the three languages. Alignment parameter τ is estimated in this step.
5. Functional Data Analysis II: Modeling the f_0 contour of the continuation rise portions, using fourth-order polynomials. Shape parameters of the continuation rises are estimated in this step.

For these steps we use a variety of standard signal processing tools: *sox*, *ffmpeg*, *ESPS*, and *GNU Octave* (Eaton et al., 2019), a public-domain package that is similar to *Matlab* in its syntax and functionality. Subsequent statistical analysis of the modeled contour features was carried out in *R*.

Standardization of audio file formats.

All our data sources were digital, in a variety of formats (e.g., mp3, mp4, and .wav PCM; 2-channel or monophonic), bit rates or sampling rates (e.g., 44.1 kHz, 22.05 kHz, or 16 kHz). Additionally, some digital recordings made from ¼-inch tape, recorded at different tape speeds, required speeding up or slowing down by a factor of 2 or ½ to restore the correct original recording rate. A small number of such digitized tape recordings ran backwards on one channel as the tape spool had originally been turned over for the second half of a monophonic recording, but it had been digitized as if it were a two-track stereo recording. To permit for the subsequent functional data analysis steps to be performed as batch computations, we converted all the recordings to 16 kHz, monophonic, uncompressed PCM .wav audio files.[3]

Identification of utterances containing continuation rises.

With the assistance of native speaker researchers, we employed pragmatic criteria for choosing the utterances we would analyze in all three language varieties to avoid the circularity that would ensue had we based our selection solely on intonational features. The included phrases were parts of broad focus declaratives in which no constituent carries narrow focus, which were nonfinal in the speaker's turn, and ended in a high boundary that typically (but not always) was followed by a short pause. In some cases, this high boundary tone was followed by a slight fall in pitch, but we took the closeness of the high tone to the end of the phrase as the only intonational criterion; the internal intonational details of the phrase were not used for the selection.

For each variety, the native speaker researchers identified the relevant utterances, orthographically transcribed them, translated them into English, located the nuclear word and manually annotated the beginning and the end of the stressed vowel ("v") using *Praat* (Boersma & Weenink, 2020) as in Figure 3 (top). The start of this stressed vowel served as the beginning of the "Region of Interest," that is, the part of the continuation rise tune compared across all three languages extending from the start of the vowel to the end of the utterance.

Estimation and verification of f_0 contours.

For each utterance, f_0 was measured every 10 ms (1 cs) using the *ESPS (Entropics Signal Processing System) get_f0* function (Talkin, 1995), to obtain an f_0 time series.

To identify f_0 tracking errors, especially octave doubling and halving, and to provide a degree of normalization of between-speaker differences in voice pitch, the f_0 contours of each utterance were converted to semitones above or below the whole utterance mean, $\bar{f}_0$, as in (1). This makes every token directly comparable to all the others and goes some way to normalizing for interspeaker differences. If the data had included better information about speaker identities, we might preferably have transformed f_0 to semitones above or below the speaker mean, but we lack that data.

$$f_0[\text{semitones}] = 12/\log_{10}(2)\log_{10}(f_0[\text{Hz}]/\bar{f}_0[\text{Hz}]) \qquad (1)$$

Given this transformation, an octave error is a sudden jump of twelve semitones (or thereabouts; it can be twelve semitones + some small change in f_0), as shown in Figure 3. All such potential octave jumps were individually inspected to check that they were octave errors, not actually occurring large pitch changes; the error portions were then corrected by doubling or halving (as appropriate) the f_0 measurements throughout the mistracked interval. Other large or sudden jumps in f_0 were similarly inspected to determine their cause. Rapid pitch perturbations due to consonantal onsets or offsets were retained unaltered as they are a natural part of f_0 contours. In other cases, rapid jumps could be attributed to environmental noises or to other speakers; such portions were zeroed out in the measured f_0 tracks.

Modeling the f_0 contours of whole utterances.

To determine differences or changes in the shape of continuation rises, we employ techniques of Functional Data Analysis (Ramsay, Hooker, & Graves, 2009), a statistical approach to analyzing continuous data such as curves, signals, or surfaces used in a broad spectrum of disciplines such as physiology (growth curves), demographics (population variables), weather forecasting, and, more recently, speech (Andruski & Costello, 2004; Aston et al., 2010; Chen & Wang, 1990; Grabe et al., 2005, 2007; Gubian, Cangemi, & Boves, 2011; de Ruiter, 2011; Zellers et al., 2010).

Functional data analysis begins with data smoothing and fitting to a selected "basis function," a process that transforms a time series of discrete, raw data points (in this case measured f_0 values) into a smoothly varying function. This emphasizes patterns
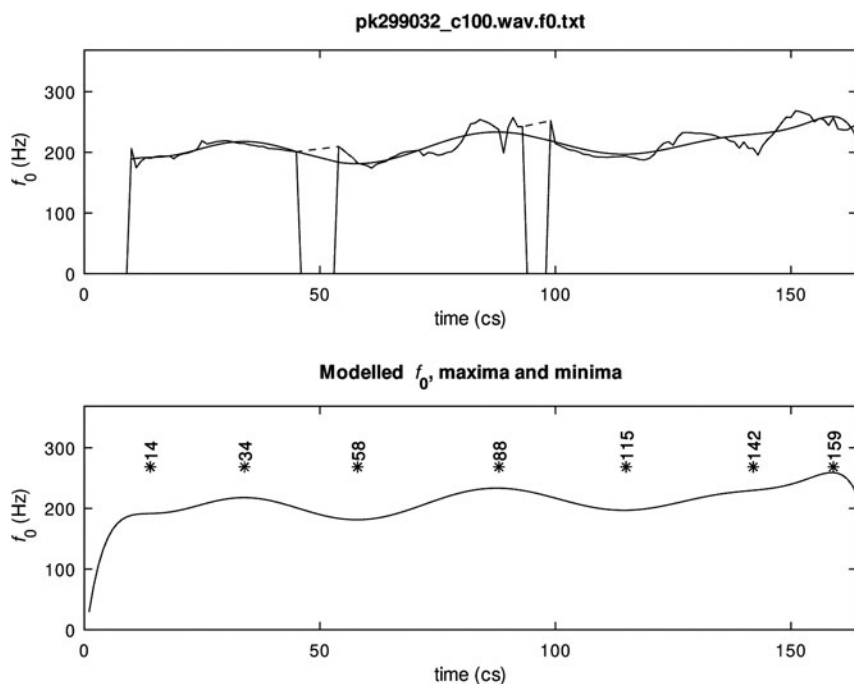
pk299032_c100.wav.f0.txt

Modelled f_0, maxima and minima

Figure 2. An example of a tenth-order polynomial fitted to the f_0 contour of an utterance. Top: the smooth modeled curve is superimposed on the observed curve, which is characterized by rapid pitch perturbations, some due to consonantal onsets or offsets. Note the two voiceless stretches in the observed data at around 50 and just before 100 cs. Bottom: The modeled f_0 maxima and minima locations are indicated by stars at the relevant times.

in the data by minimizing short-term deviation due to measurement errors or inherent system noise. Functional data also allows information on the *shapes* of the curves to be obtained, which facilitates comparisons across languages, language varieties, genders, generations of speakers, and other sociolinguistic or phonetic variables. A significant advantage of functional data analysis is that it augments the highly abstract and impressionistic Autosegmental-Metrical analysis of intonation with quantitative, empirically testable models of tunes, allowing comparisons of large numbers of pitch curves of whole utterances or their parts and facilitating the study of melodic variability, co-occurrence of patterns of tone combinations in melodies, and their frequency of occurrence.

Tenth-order polynomials (2) were then fitted to the f_0 contours using the GNU Octave/Matlab *polyfit* function (Eaton et al., 2019).

$$f_0[\text{fitted}] = \Sigma a_n t^n \text{ for } n = 0, \ldots, 10 \qquad (2)$$

Tenth-order polynomials were used to fit the f_0 contour of utterances that may be long, with up to nine peaks and troughs (e.g., Figure 2 top). That was sufficient for this dataset; in longer utterances with more than nine peaks and troughs, an even higher-order polynomial could be used.[4]
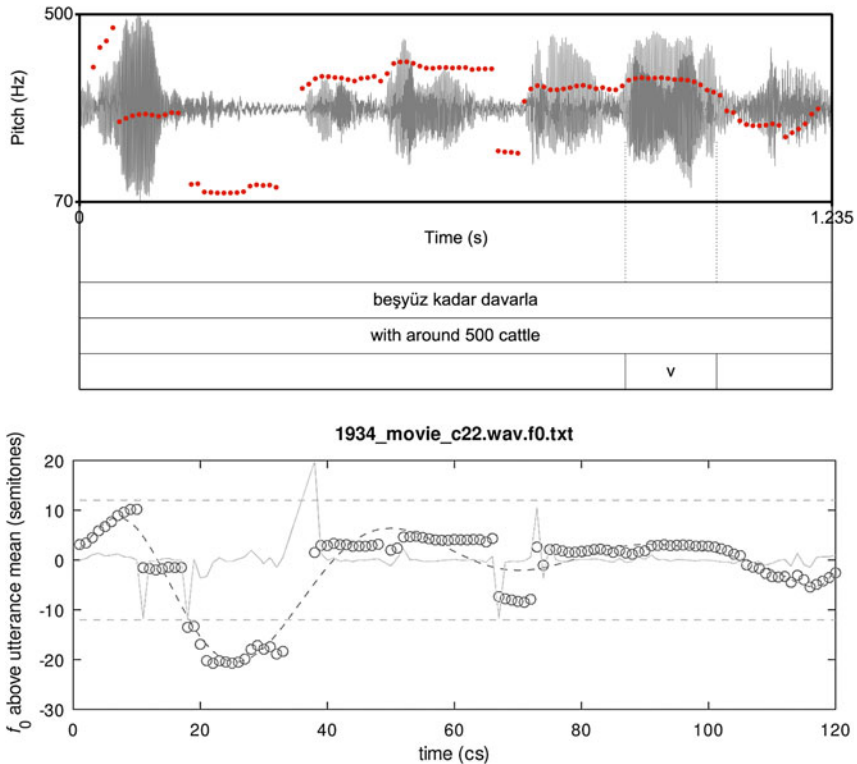
Figure 3. Top: *Praat* waveform with a pitch track exhibiting several octave errors. Bottom: The observed pitch track (circles), the modeled curve fitted to the pitch track (dashed curve) and the difference between observed data and polynomial model (solid grey line). Such octave errors are indicated by a spike in the difference signal (solid grey line) reaching either of the two faint grey horizontal dashed lines (showing a difference of ±12 semitones). The pitch track shows three octave jumps downwards at around 10, 20, and 70 cs. The large jump upwards of 20 semitones at around 35 cs is a 12-semitone restoration of the previous pitch tracking error, added to a genuine f_0 movement of 8 semitones. The jump upwards at around 75 cs is a return from the previous error at around 70 cs.

Fitting a specific polynomial function to the data also permitted us to find the peaks and troughs in the f_0 contour analytically, by differentiating (2), since they lie at points where its first derivative (3) is zero.[5]

$$\mathrm{d}f_0/\mathrm{d}t = 10a_{10}t^9 + 9a_9t^8 + \ldots + a_1 \tag{3}$$

The roots (values of t at which $\mathrm{d}f_0/\mathrm{d}t = 0$) were found using the *GNU Octave/Matlab* function *real(roots(polyder(a)))*. These roots provide the times of all the maxima and minima (peaks and troughs) of the intonation contour (Figure 2 bottom). Putting these times back into equation (2) gives the f_0 of those peaks and troughs.

Since there are nine such turning points in a tenth-order polynomial, we manually selected the first local minimum after the start of the nuclear vowel in each continuation rise for the alignment comparison. As this local minimum is present in all

the three varieties, this choice ensures crosslinguistic comparability. We determined the alignment (τ) of this local minimum to a segmental landmark, the end of the nuclear vowel; specifically, $\tau = t(\min f_0) - t(V \text{ end})$. $\tau > 0$ means that the trough follows the end of the nuclear vowel (Turkish pattern) and $\tau < 0$ means that the trough precedes the end of the nuclear vowel (Athenian pattern).

Thus, polynomial modeling enables us to calculate very precisely the location of peaks and troughs in the f_0 track. Prior work on intonation has often found it difficult to estimate the location of such turning points due to the presence of voiceless stretches or microprosodic perturbations (e.g., the voiceless stretches in Figure 2), finding recourse instead in specially designed laboratory utterances containing mostly sonorant segments. Simply picking maxima and minima of observed f_0 is a rather questionable and inexact method (Kochanski, 2010). The location of a high or low f_0 "target" may coincide with a portion of voicelessness in the speech signal, and the observed f_0 contour will not have a measured value at such a point. In contrast, the method used here is able to infer an estimate of the peak or trough location and its modeled f_0 value even during intervals of voicelessness.

Modeling f$_0$ in the Region of Interest/continuation rise portions.

The Region of Interest, as defined in Identification of utterances containing continuation rises section, contains from one to three syllables, depending on the variety and stress position (antepenultimate, penultimate, or final). To characterize similarities or differences in the overall shapes of the continuation rises in the Region of Interest, we visually inspected the shape of f_0 in this region. The most complex shape involved two peaks and a trough, and therefore the f_0 in this region was modeled in further detail using fourth-order polynomials, an order of polynomial that is necessary and sufficient for a model that has three extrema.

We then modeled the normalized f_0 data using polynomial basis functions, following Grabe et al. (2007). This process converts discrete data points (f_0 values) into a smoothly varying, continuous function, that is,

$$f_0 = a_4 t^4 + a_3 t^3 + a_2 t^2 + a_1 t + a_0 + \varepsilon \tag{4}$$

for the fourth-order case (Figure 4), one among various possibilities. The values of constants a_0 to a_4 were found using the *GNU Octave/Matlab polyfit* function.

Disregarding the error term ε, the modeled f_0 function in (4) was then converted into the corresponding form (5), the best-fitting sum of Legendre polynomials.

$$f_0[\text{fitted}] = c_4 L_4 + c_3 L_3 + c_2 L_2 + c_1 L_1 + c_0 L_0 \tag{5}$$

This transformation has the benefit that the c_n coefficients of each term are orthogonal, unlike the a_n coefficients of an ordinary polynomial such as (4). Low-ranking terms of a polynomial pick out slowly varying properties, and higher-ranking terms pick out successively more rapidly varying properties. Legendre polynomial L_0 models the overall level or height (roughly, the average) of the delimited portion of the data, L_1 models the slope of that extract, L_2 fits a parabola to the
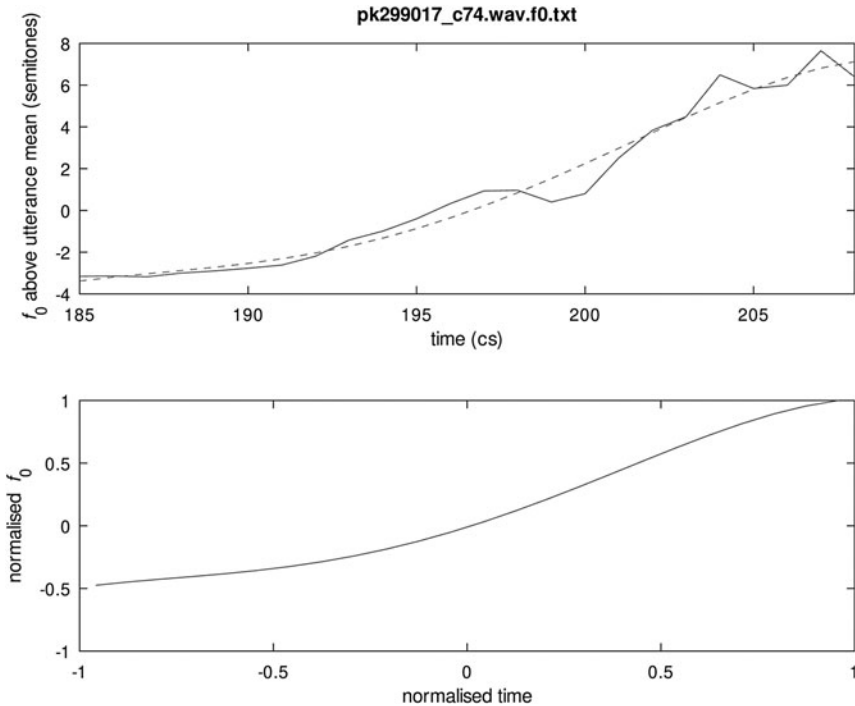
Figure 4. Fourth-order polynomial fitted to the region of interest of an AMG continuation rise, the f_0 contour from the beginning of the nuclear vowel to the end of the utterance. Above: the smooth modeled f_0 curve (dashed line) is superimposed over the observed data (continuous line). Below: The same fitted curve with axes normalized to the interval $[-1, 1]$.

data, L_3 models the data as an up-down-up (or down-up-down) wavy shape, and L_4 as a more complex wavy m- or w-shape. If the sign of the respective c_n coefficient is inverted, those components of the pattern are flipped upside down about the horizontal axis (see Grabe et al. [2007] for further details).

We refer to the coefficients of the lowest four components as AVERAGE (i.e., c_0), SLOPE (c_1), PARABOLA (c_2) and WAVE (c_3) (see Grabe et al. [2007]), and coefficient c_4 as M-OR-W. The orthogonality of these components, coupled with the simplicity of their shapes (unlike, for example, Principal Components), makes the physical interpretation and particular contribution to the overall f_0 contour quite straightforward and intuitive. Other basis functions are of course possible, but we consider the independent prosodic transparency of these components to be an appealing feature of this methodology.

Legendre polynomials take values in the range $[1, -1]$, so corrected f_0[semitones] was scaled so that the whole f_0 contour lies within the interval $[1, -1]$, with 0 as the utterance mean and the greatest positive or negative deviation from the mean being 1 or -1, as the case may be:

$$f_0[\text{normalized}] = f_0[\text{semitones}]/\max(|f_0[\text{semitones}]|) \qquad (6)$$

As a consequence of this step, the normalized average f_0 of every utterance $= 0$; f_0 [normalized] > 0 means "higher than average f_0", f_0[normalized] < 0 means "lower than average f_0" (see Figure 4, lower panel, for an example).

The c_n coefficients are calculated from the a coefficients through a set of simple formulae, the details of which vary according to the order of the polynomial.[6] The normalization or scaling needed for the transformation to Legendre polynomials reduces interspeaker variation, to some extent. In particular, it reduces individual differences in mean f_0, f_0 range, and speech rate. But we are not interested in those parameters in this study; the normalization and scaling do not affect interspeaker differences in the *shape* of the intonation contours, represented by the c_n coefficients, and we examine the relative timing of the pitch peaks and troughs using the a_n coefficients of the standard polynomial (4), prior to scaling.

Figure 5 presents orthogonal polynomial analysis of prototypical examples of Athenian and Turkish continuation rise contours, showing each of the five polynomial terms independently. The same scale is used for both varieties in order to show their differences in magnitude. The Athenian example, at left, is a typical L* H− contour with a slight initial descent, a low plateau, and a large final rise. The magnitudes of the M-OR-W and WAVE components are therefore almost 0, and those components are almost flat. PARABOLA and SLOPE are much larger; the size of the PARABOLA coefficient c_2 gives a broad and rather shallow bowl shape. The strong overall rising profile of this intonation contour is mostly determined by the positive SLOPE component.

The Turkish example (Fig. 5 right) is quite different, a typical rise-fall-rise, with a slight deceleration/flattening off at the very end. Consequently, the WAVE component is large, more than ten times the magnitude of the WAVE component in the Athenian example. It is positive, meaning that it is a rise-fall-rise. The PARABOLA component is the largest and is over eight times larger than in the Athenian example, giving this component a narrower trough in Turkish than in Athenian. The M-OR-W component is negative, giving it two peaks rather than two troughs (M-like rather than W-like); the second of those peaks captures the slight flattening-off of the final rise. The AVERAGE component in the Turkish pattern is higher than in the Athenian pattern, because Turkish has two large peaks whereas Athenian has a long low plateau that is mostly a few semitones below the average.

To appreciate the individual contributions of the five components further, appendix B provides further illustrations of the same two examples in which each component is set to zero, one by one.

Hypotheses

Four hypotheses were tested. H1 (geographic region): based on impressionistic analysis, no differences are expected in the intonation patterns of the continuation rise tune between the regional varieties of Turkish. H2 (diachronic development): based on Baltazani et al. (2020), the intonation of AMG speakers is expected to display a mixture of Athenian-like and Turkish-like patterns. In addition, H3: first-generation AMG speakers are expected to make more use of Turkish-like patterns and less use of Athenian-like patterns than the subsequent generations. H4:
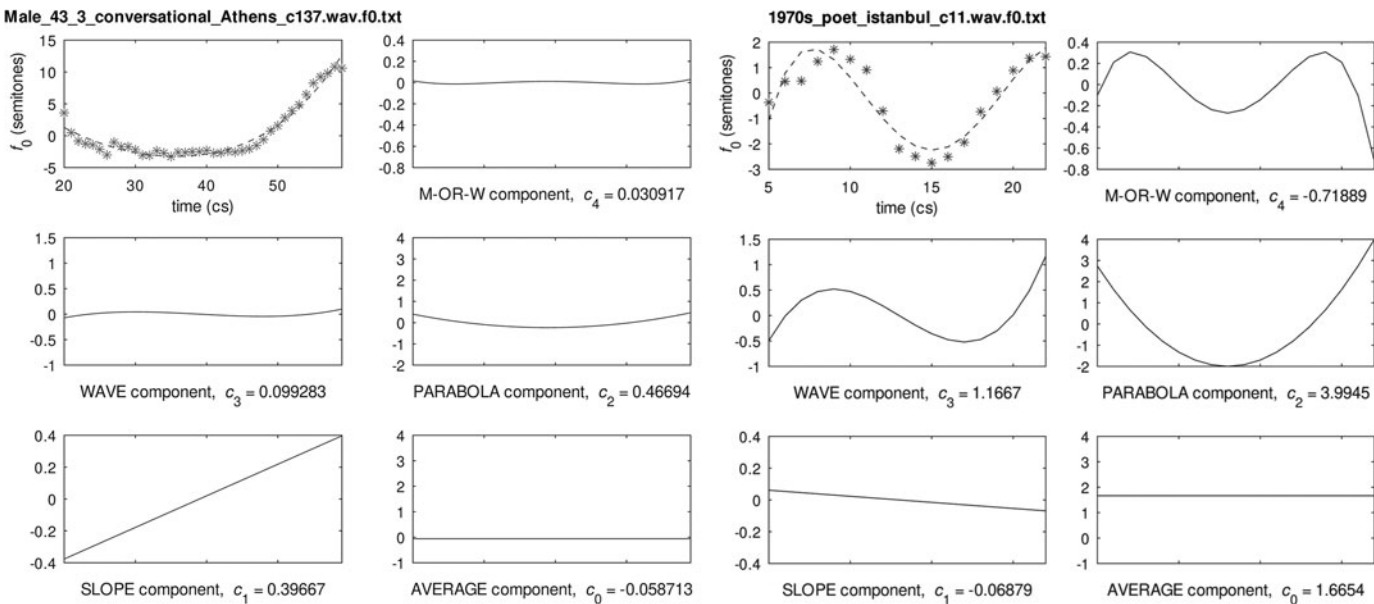
Figure 5. Fourth-order orthogonal polynomial components of typical examples of Athenian and Turkish continuation rise contours.

similarities between AMG and Turkish are expected to diminish with each subsequent generation.

Based on the prior literature on continuation rises in Athenian and Turkish, we expect any influence of Turkish on AMG to be manifested in the shape of the modeled curves, through similarity in the polynomial coefficients. For example, because Turkish displays a rise-fall-rise f_0 movement while Athenian displays a simple rise from a trough, we expect Turkish-like continuation rises to have a positive WAVE coefficient that models the data as an up-down-up wavy shape and Athenian-like ones to have a WAVE coefficient around zero, that is, no such wavy shape, though we would expect Athenian-like continuation rises to have a positive SLOPE. In addition, we expect the alignment of the trough in the Region of Interest to be relevant: the nuclear accent in Athenian is typically realized as a trough aligned within the nuclear vowel ($\tau < 0$), while the H*+L nuclear pitch accent in Turkish is realized with an H* tone within the nuclear vowel followed by the trough, a trailing L tone, which typically occurs after the end of the nuclear vowel ($\tau > 0$).

Statistical analysis

Because there were relatively few archival recordings of first generation AMG speakers, we pooled data from archival recordings made in the 1920s and 1930s and contemporary ones made in the 2000s, having first checked that there were no significant differences between the two types. Baltazani et al. (2020) tested the hypothesis that the influence of Turkish would be found to be greater in the archival than in the contemporary recordings. Turkish influence was expected to have diminished in contemporary recordings due to longer contact with Greek (eighty years between 1930 and 2011) and absence of contact with Turkish. A Mann-Whitney U test revealed no significant difference in the curve shape (e.g., for c_3, U = 13,452, p = .518; for c_2, U = 12,656, p = .129) or in the alignment (U = 13,317, p = .427) between archival recordings (mean ranks c_3 = 173, c_2 = 166, alignment = 184) and contemporary recordings (mean ranks c_3 = 181, c_2 = 184, alignment = 175).

For the geographic region comparison, six Kruskal-Wallis one-way analyses of variance (Kruskal & Wallis, 1952) tested for differences between the Turkish regional varieties in the five polynomial coefficients (c_4 to c_0) and trough alignment (τ).

For the diachronic development hypothesis, we used a *Gaussian mixture model* (e.g., Marin et al., 2005), which formalized the assumption that the distributions of shape coefficients in the AMG data are either Athenian-like (with a probability of λ) or Turkish-like (with a probability of $1-\lambda$). As ANOVAs and frequentist linear mixed effects models are more widely used in phonetics research, the choice of a (Bayesian) Gaussian mixture model may warrant justification. The main reason is that we were not only interested in whether the coefficients varied by generation or dialect (as an ANOVA would allow us to detect). To test hypothesis 4, we also wanted to determine the relative proportions of Turkish-like and Athenian-like utterances in AMG in each generation, since we had previously found that our first generation of AMG speakers used a mixture of Athenian-like and Turkish-like patterns (Baltazani et al., 2020).

In consequence, the distributions of coefficients for every AMG speaker were assumed to be a mixture of an Athenian-like component and a Turkish-like component, scaled by the mixture proportion λ, as illustrated in Figure 6 for different examples of mixture distributions with different mixture proportions λ (left, center, and right panels) and different distances between the modes of the two components that constitute the mixture (upper and lower panels). Figure 6 also illustrates that not all mixture distributions are evidently bimodal: when the two mixture components (dotted and dashed lines, respectively) are sufficiently far away from each other relative to their variance, the resulting mixture distribution does have two clearly visible modes regardless of the mixture proportion parameter λ (panels A-C). In contrast, when the mixture components are close, with significant overlap between them, there might be only one local maximum in the mixture distribution (panels D and F). The presence of distinct modes depends on the mixture proportion λ and the distance between the distributions.

While the distributions of some coefficients for the AMG data were bimodal (as shown in Figure 9 below), similar to those in panels A-C in Figure 6, some had a single local maximum. Even in such cases, mixture proportions can be estimated if the distributions of the mixture components are known. Thus, we modeled the distribution of AMG coefficients as a mixture of Athenian-like and Turkish-like distributions. To this end, we assumed that the coefficients for Athenian and Turkish tunes were normally distributed with means μ_A, μ_T and standard deviations σ_A, σ_T, while AMG followed a mixture of the distributions[7] $N(\mu_A, \sigma_A)$ and $N(\mu_T, \sigma_T)$ with different mixture proportions λ_g for each generation g.

We further assumed that λ_g represents the proportion of Athenian-like *utterances* in a given generation rather than the proportion of Athenian-like *speakers*. This is because most AMG speakers produced continuation rises with both Athenian-like and Turkish-like patterns, as illustrated in the two examples in Figure 7, which were produced by the same speaker.

A more detailed description of the model structure is presented in appendix C.[8] All free model parameters (μ_A, μ_T, σ_A, σ_T, λ_1, λ_2, λ_3, λ_4) were estimated from the data using a Bayesian model implemented in *brms* (Bürkner, 2017) and *rstan* (Stan Development Team, 2022a, 2022b) in *R* (R Core Team, 2021) with by-speaker random effects for the means of the speaker-specific Athenian-like and the Turkish-like coefficient distributions μ_A and μ_T, accounting for the fact that each speaker's scores could be systematically lower or higher than the group averages.

To establish the validity of the Gaussian mixture model, we compared it to a baseline model for each coefficient (c_0 to c_4), and τ, the trough alignment. As a baseline, we used Bayesian linear mixed-effects models (e.g., Gelman & Hill, 2006; Vasishth & Nicenboim, 2016) with generation, dialect, and their interaction as fixed effects, and by-speaker random intercepts. A detailed description of the model structure is presented in appendix D. We compared the models based on their *expected log pointwise predictive density (elpd)*, calculated using PSIS-LOO CV in the *R loo* package (an implementation of Vehtari, Gelman, & Gabry, 2017). The *elpd* statistic provides an estimate of a model's out-of-sample performance and thus implicitly penalizes excessive model flexibility, thus putting models of different complexity on an equal footing.
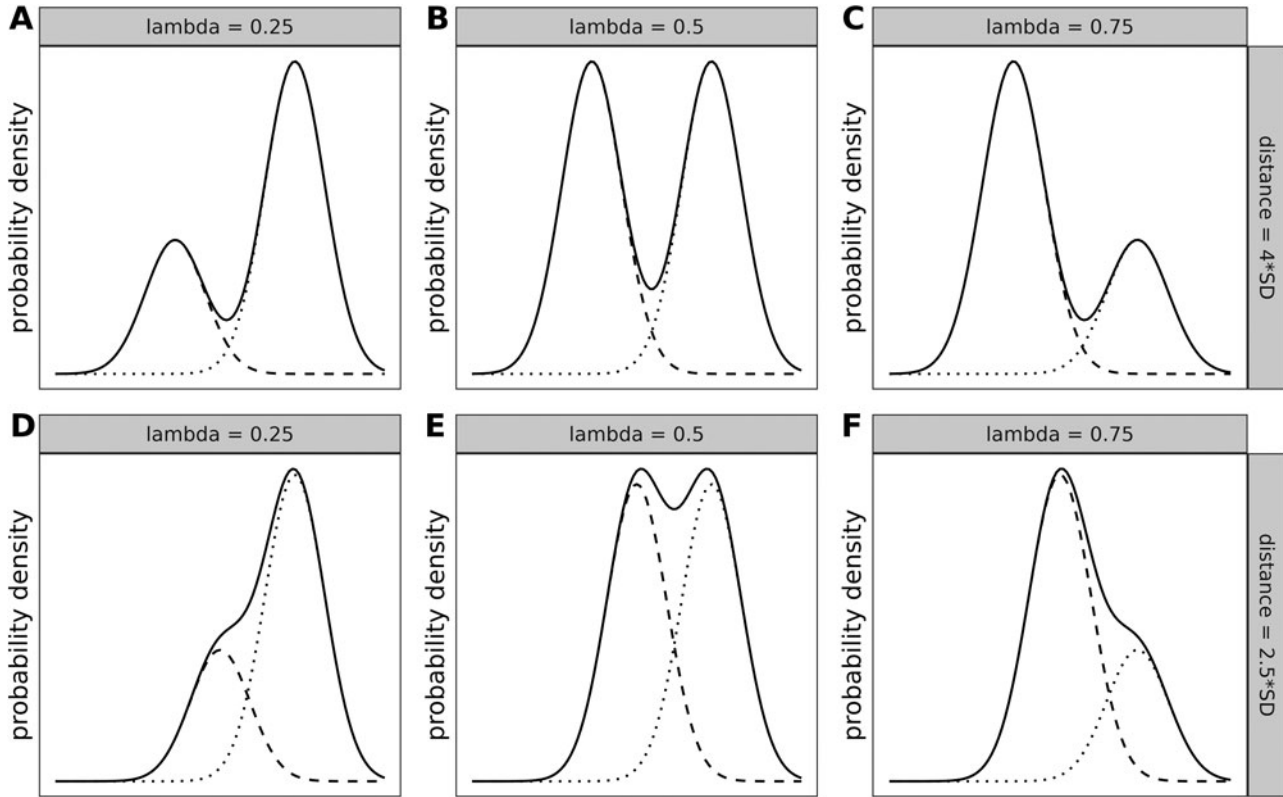
Figure 6. Probability density functions of hypothetical mixture distributions (solid lines), and their component distributions (dotted and dashed lines), for different mixture parameters λ (columns) and different distances between the modes of the mixture components (rows).
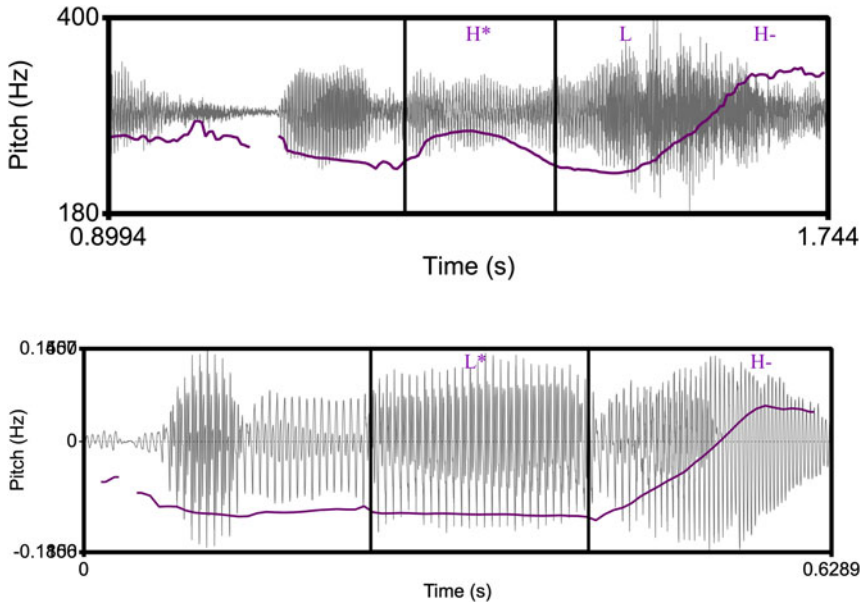
Figure 7. Examples from the same AMG generation 1 speaker producing a Turkish-like (top) [isto'ria] "…story…" and an Athenian-like (bottom) [ta'meri] "The places" continuation rise. Rectangles indicate the nuclear vowel, transcribed in bold.

Results

Geographic region comparison

There was very strong evidence of differences between the Turkish geographic varieties for four coefficients: M-OR-W (c_4; $\chi^2(4)= 105.31$, $p < 0.001$), PARABOLA (c_2; $\chi^2(4)= 89.46$, $p < 0.001$), SLOPE (c_1; $\chi^2(4)= 14.26$, $p = 0.007$) and AVERAGE (c_0; $\chi^2(4)= 101.93$, $p < 0.001$), adjusted using the Bonferroni correction, but no difference between the varieties for the WAVE coefficient c_3 and the alignment parameter τ.

Each group's mean and median values are also important for the interpretation of these results. As mentioned in the section *Modeling f_0 in the Region of Interest*, the sign of each coefficient is important because the patterns of coefficients with negative values are flipped upside down. The median values for each coefficient in the Turkish data (Fig. 8) have the same sign across the varieties, indicating no difference in *shape* for the parameters, despite the significant differences in their magnitudes. In view of this, in combination with the fact that all these tokens have the same meaning of continuation rise, we interpret the results of statistical significance as phonetic microvariation. That is, the same phonological pattern for the continuation rise tune is displayed for every coefficient in all varieties (corresponding to the H*+L H− tune), though there are fine phonetic differences, for example, in the breadth of the curvature or the steepness of the slope.

For the subsequent analysis, data from all five varieties were grouped together because no phonological differences were found between them.
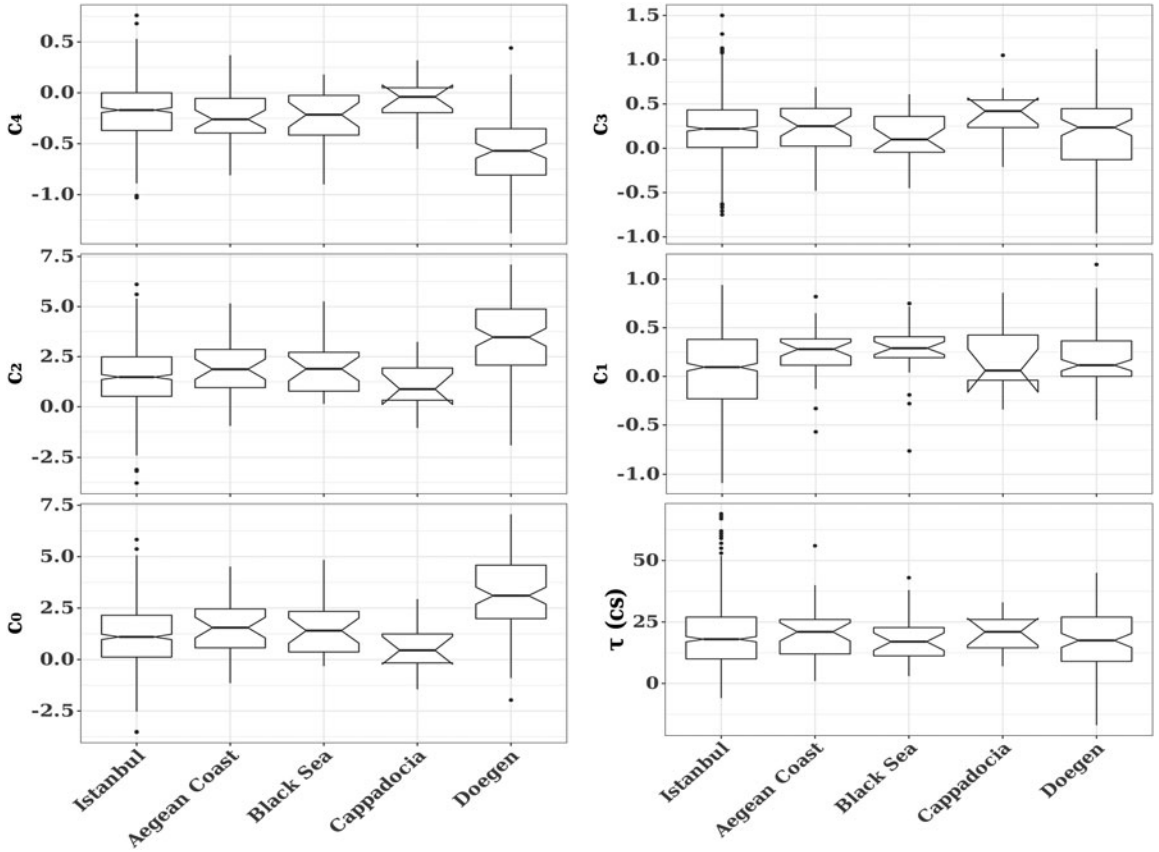
Figure 8. Comparison (from top left to bottom right) of M-OR-W, WAVE, PARABOLA, SLOPE, AVERAGE coefficients and trough alignment in continuation rises produced by Turkish speakers of five different regional varieties (Turkish speakers in the Doegen archive were from the Ottoman Empire, in present-day Romania).

Diachronic comparison

Figure 9 shows the distribution and variation of the coefficients and trough alignments for each generation in AMG, Athenian, and Turkish (in each panel, upper, middle, and lower rows, respectively). Vertical dashed lines superimposed on the histograms correspond to the medians of the observations for Athenian and Turkish. The histograms for AMG are overlaid with both the Athenian and Turkish median lines to indicate the approximate position of the expected modes if the mixture were bimodal.

In Athenian and Turkish, the coefficient medians, for all generations, confirm the impressionistic descriptions of the tunes in 2.1. The positive SLOPE coefficient c_1 for Athenian indicates a rise, but the 0 for Turkish is the average of a rise-fall-rise, the shape of which is captured by other parameters. The positive PARABOLA coefficient c_2 for Turkish models the data as an accelerating f_0 movement, and the 0 for Athenian indicates that this parameter does not contribute much to the contour, mostly a low plateau. The WAVE c_3 is positive for Turkish, modeling the data as a rise-fall-rise f_0 movement, but it is close to 0 for Athenian, indicating that it is not so wavy: it is a plateau plus a rise. The median of the M-OR-W coefficient c_4 is negative in Turkish, reflecting the fact that it has two peaks: an H accent on the stressed vowel followed by a trough and then another peak at the end of the utterance. The median M-OR-W is close to 0 in Athenian as it does not have two peaks. The median alignment parameter τ is negative for Athenian, showing that the L tone is aligned *before* the end of the stressed vowel (approximately twenty cs), and is positive for Turkish as the L tone is aligned approximately twenty cs *after* the end of the stressed vowel (Fig. 9).

The AMG histogram reveals a shift from greater use of Turkish-like patterns to greater use of Athenian-like patterns over the generations. The distribution of the SLOPE c_1 coefficient (top row in Fig. 9), has a mode in between the Turkish and Athenian medians. Figure 10 shows that the median SLOPE for AMG changes over the four generations, becoming progressively more Athenian-like. The next two rows in Figure 9 show that the PARABOLA c_2 and WAVE c_3 coefficients have a bimodal appearance in the first-generation. One peak of the AMG distribution is near to the Athenian median and the other is near to the Turkish median. Over the generations, the Turkish-like peak becomes smaller, so that these distributions have an increasingly unimodal appearance as the proportion of Turkish-like values seems to decrease, a pattern like the one modeled in Figure 6F. The M-OR-W coefficient c_4 also changes across the generations: the AMG mode always coincides with the Athenian mode, but the AMG distribution is substantially wider than the Athenian with a tail toward Turkish values, a pattern as in Figure 6D. The Turkish-like aspect of this tail in the first generation is reduced in subsequent generations.

The bottom row of Figure 9 gives the visually most striking finding: the distribution of the L tone alignment τ is clearly bimodal in the first three generations, the two peaks in the first generation almost coinciding with the medians of Athenian and Turkish, as in Figure 6B. For this parameter as well, the proportion of Turkish-like values decreases over the generations, giving rise to a more Athenian-like distribution, similar to Figure 6F.
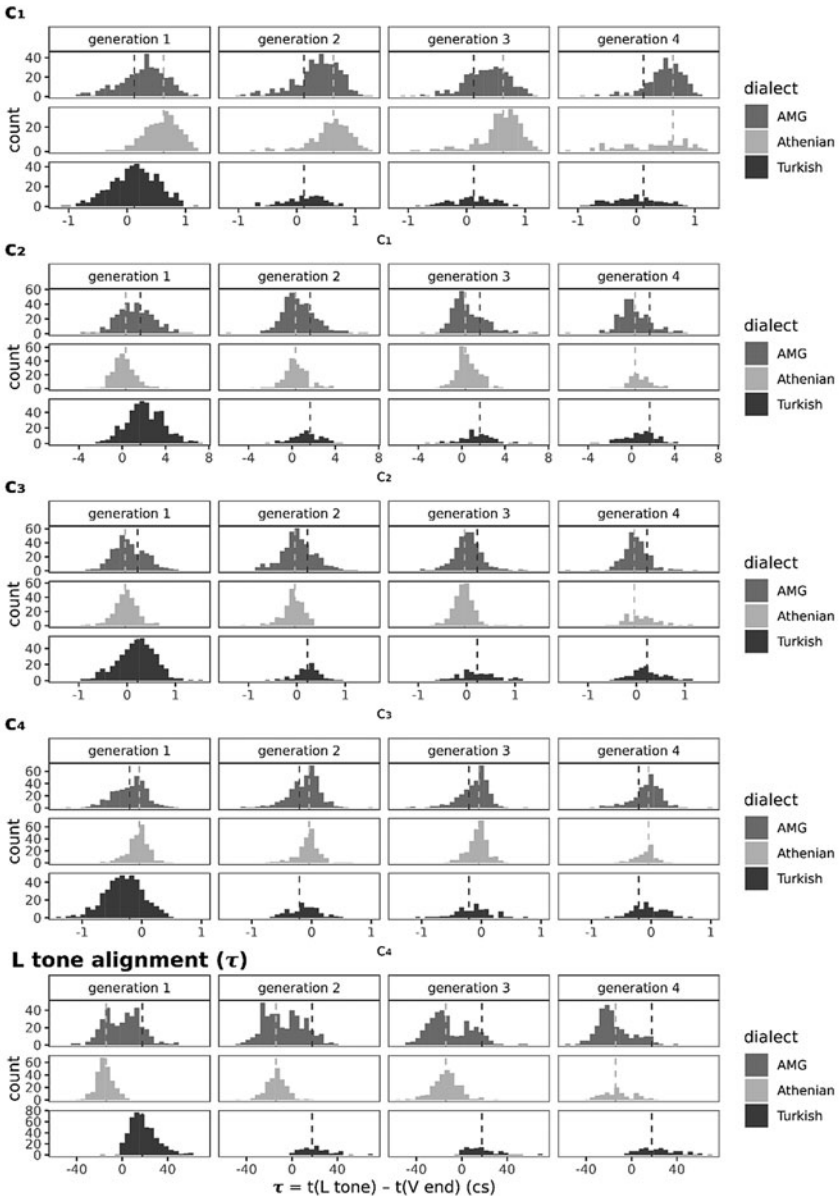
Figure 9. Histogram of coefficients c_1 to c_4 and L tone alignment τ by dialect and speaker generation. Vertical dashed lines correspond to the medians of the observations among speakers of Athenian (light grey) and Turkish (dark grey) over all generations. The histogram for AMG (mid grey) is overlaid with both median lines, for reference.

In view of the above, we compared a Bayesian analysis of the Gaussian mixture model with a baseline linear mixed effects model for all five dependent variables as described in 2.6. The results of the model comparison using PSIS-LOO CV are

Figure 10. Estimates of λ, the proportion of Athenian-like utterances, for each generation. Circles indicate the median of the 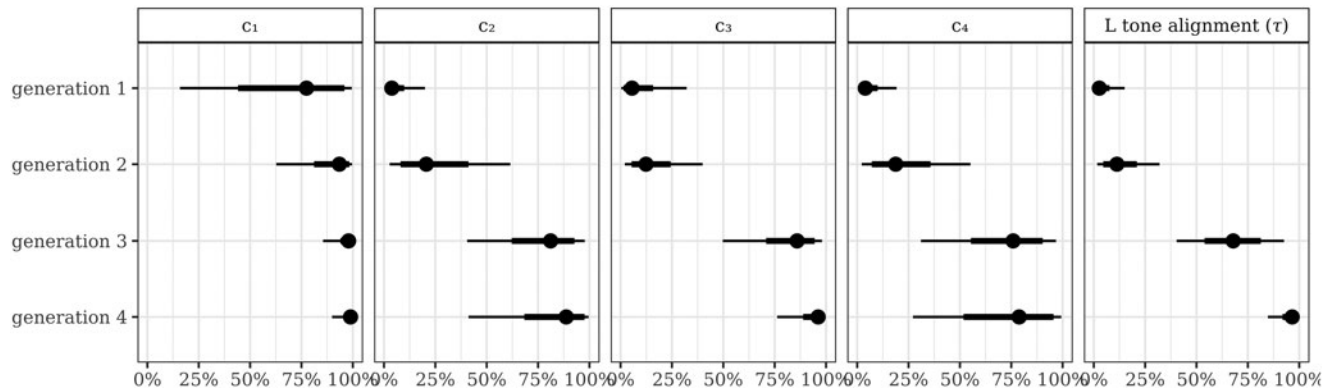posterior distribution, thin horizontal lines represent the 90% credible intervals of each parameter estimate, while thick horizontal lines indicate 60% credible intervals.

Table 2. Results of the model comparisons between (i) the baseline linear mixed effects model and (ii) the Gaussian mixture model for the coefficients c_1-c_4, and τ using PSIS-LOO CV estimates of elpd (Vehtari et al., 2017). Larger elpd$_{LOO}$ values indicate more parsimonious models. Positive Δelpd$_{LOO}$ values indicate that the Gaussian mixture model provides a more parsimonious account than the baseline linear mixed-effects model

	elpd$_{LOO}$, baseline model	elpd$_{LOO}$, mixture model	Δelpd$_{LOO}$, mixture − baseline
c_1	−1195.1 (SE=46.1)	−1179.3 (SE=47.6)	15.8 (SE=11.8)
c_2	−5233.3 (SE=48.2)	−5125.8 (SE=48.5)	107.6 (SE=17.6)
c_3	−691.8 (SE=48.1)	−603.0 (SE=50.1)	88.8 (SE=18.6)
c_4	−29.5 (SE=49.6)	110.0 (SE=49.7)	139.5 (SE=20.3)
τ	−12083.4 (SE=42.5)	−11944.6 (SE=44.6)	138.8 (SE=23.1)

presented in Table 2. They show that the mixture model provided a better description of the data than the linear mixed effects model for all parameters. The mixture model only weakly outperformed the baseline model for c_1 but showed a substantial improvement over the baseline for the rest of the parameters.

In the Gaussian mixture model, estimates of the mixture parameter λ (proportion of Athenian-like values, expressed as a percentage) for the remaining parameters are shown in Table 3 and Figure 10. Several trends are revealed for all parameters except SLOPE c_1. First, the median estimates of λ are very close to Turkish values (less than 7% Athenian-like) in generation 1. Second, in generation 2, the median estimates of λ are gradually approaching Athenian (11% - 21% Athenian-like). Third, the median estimates of λ in generation 3 are over 68% Athenian-like. Among all the parameters we examined, only c_1 showed higher Athenian-like values than Turkish-like values. Yet, the rate of this similarity increased gradually from the first-generation to the-fourth generation as well.

All in all, these results reveal a consistent pattern of a change over the generations in the realization of continuation rise tunes. The strong similarity to Turkish in AMG generation 1 weakens over the generations, with Athenian characteristics becoming predominant in generations 3 and 4.

Table 3. Mean estimated proportion (λ) of Athenian-like parameter values in AMG by generation (left column) and 90% credible interval (CI; right column)

	SLOPE c_1		PARABOLA c_2		WAVE c_3		M-OR-W c_4		ALIGNMENT τ	
Gen	λ	CI	λ	CI	λ	CI	λ	CI	λ	CI
1	77%	8−100%	4%	0−29%	6%	0−44%	4%	0−26%	3%	0−19%
2	93%	53−100%	21%	2−71%	12%	2−48%	19%	2−64%	11%	1−39%
3	98%	79−100%	81%	32−99%	86%	40−99%	76%	22−98%	68%	35−95%
4	99%	83−100%	89%	29−100%	96%	64−100%	79%	18−100%	97%	77−100%

Discussion

In this paper, we examined how long contact effects in intonation persist after contact has ceased. We compared the f_0 patterns in continuation rise tunes of Athenian Greek, Turkish, and Asia Minor Greek (AMG) across four generations. We modeled the sampled f_0 data using Legendre polynomial basis functions to characterize similarities or differences between these varieties in the final stretch of the continuation rises, comprising the nuclear pitch accent and the edge tones. This modeling allowed the analysis of a fairly large dataset of approximately three thousand continuation rise utterances from diverse corpora containing mostly natural speech in conversations and narratives.

Using fitted polynomials for the analysis and comparison of the tunes in the three language varieties captures simple properties of the fitted curves and has an easily understood, cognitively plausible interpretation, such as the average f_0, whether the contour is generally rising or falling, the size and location of intonation peaks and troughs, as well as the number of peaks and troughs in the intonation contour. Furthermore, the functional data analysis can be related to the well-established Autosegmental-Metrical analysis of intonation: the derivative of the quartic polynomial used here has three roots, corresponding to the time-points of the two peaks and the trough, which allow us to estimate their corresponding f_0 more reliably than through the observed peaks and troughs, which are susceptible to noise and mistracking, especially if they occur during voiceless intervals.

The results of the diachronic comparison across four generations of Turkish and Athenian speakers confirmed the realization of the continuation rise tunes reported in the literature for these two languages. The Turkish continuation rise tune is reported as a rise-fall-rise H*+L H−, the H* tone in the H*+L nuclear pitch accent occurring within the nuclear vowel. In our data the median alignment τ of the trailing L tone is 200 ms after the nuclear vowel offset, and the H− phrase accent lies at the right edge of the phrase. The negative median M-OR-W c_4 coefficient in our modeling reflects the fact that the Turkish tune has two peaks, the positive WAVE c_3 captures its rise-fall-rise f_0 movement, and the positive PARABOLA c_2 captures a general rising f_0 movement. The Athenian tune also ends in an H− phrase accent but has a L* nuclear pitch accent that is aligned on average 200 ms *before* the end of the nuclear vowel. The positive SLOPE coefficient c_1 for Athenian indicates that, in general, it rises while the low plateau from the nuclear vowel to the phrase edge is reflected in the PARABOLA c_2, WAVE c_3, and M-OR-W c_4 coefficients, all of which are close to 0, indicating that the Athenian contour lacks a wavy shape, and that it does not have two peaks.

As for AMG, a previous analysis of this tune in two generations of speakers showed a dual pattern of the L tone alignment, one Athenian- and one Turkish-like. Here we established a more complete picture by showing that the mixed pattern of the data is true for all five parameters through a Gaussian mixture model. The bimodality of the L tone alignment found in the speech of the first-generation AMG speakers decreased in each subsequent generation toward a more Athenian-like alignment. A similarly diminishing proportion of Turkish-like patterns was revealed for the polynomial coefficients c_1 to c_4. While in generation 1 the

mixture coefficient λ is less than 8% Athenian-like for four of the five parameters, in generation 2 there is a greater proportion of Athenian-like coefficient values, and in the two youngest generations the greatest proportion (almost 100%) is Athenian-like.

The Bayesian approach gave us the flexibility to define a mixture model that expresses our hypotheses while allowing us to account for speaker-specific deviations from the average in the form of by-speaker random effects (e.g., Gelman & Hill, 2006; Vasishth, Nicenboim, Beckman, Li, & Kong, 2018). This approach enabled us to encode the assumption that the distribution of the AMG coefficients is a mixture of an Athenian-like and a Turkish-like Gaussian distribution, and, at the same time, estimate the mixture parameters and the uncertainty associated with them in datasets with unequal numbers of observations per speaker. For AMG speakers, all coefficients were better described by a mixture of the respective Turkish-like and Athenian-like distributions than by simple linear mixed effects models.

Contact between Greek and Turkish resulted in phonological transfer of the pitch accent found in Turkish continuation rises into AMG. The AMG speakers alternated between the Turkish and the Greek tunes in a way similar to what is reported in Queen (2012), albeit in different proportions depending on the generation. No phonetic changes such as the delayed peaks reported in O'Rourke (2012) and Elordieta and Calleja (2005) were revealed in the tunes we examined. That is, when the tune was produced with the Athenian L pitch accent, the alignment of the trough was Athenian-like, that is, within the nuclear vowel. Similar results were found for the Turkish-like tune. It is not yet clear whether these two patterns of continuation rise differ in pragmatic interpretation or whether they are codeswitched equivalents. We leave such questions for future investigation.

This paper demonstrates intonational effects of language contact, a generally understudied area, since so far the knowledge about the results of contact has mainly relied on morphosyntactic or segmental phenomena. We have shown that prosodic characteristics of Turkish have persisted in AMG for close to a century after the cessation of contact, which we attribute to the strong sense of ethnolinguistic identity in the AMG-speaking community. However, usage of the Turkish-like intonation pattern has diminished over the generations due to a complex mixture of factors such as the prestige of Athenian Greek, the stigma that some attach to AMG, and the fact that the younger generations increasingly have less exposure to their AMG heritage variety, at least the Cappadocian variety examined here, than earlier generations did.

Notes

1. Although Athenian Greek could be characterized as a new Koine (as one of the reviewers suggested), we refrain from doing so due to a lack of analytical studies to establish such a process of koineization.

2. For the majority of the sources, some metadata with sociolinguistic information were available (either directly or indirectly from public information available on the web) that included at least the speaker's age. Where information about the speaker's age was not available (marked with a star next to the token number in Appendix A) approximate age and classification to one of the four generations was inferred from characteristics of the speaker's appearance in videos or information about their career.

3. Although mp3 and mp4 files typically use audio compression with some loss of fidelity, Fuchs and Maxwell (2016:525) found that mp3 "compression rates between 56 and 320 kbps show relatively small mean errors of 2% or less, with median errors well below 0.5%. … mp3 compressed data is viable for the analysis of F0." They found that measurement errors in mp3-compressed data were greatest of all in consonants, for example, the perturbations to f_0 caused by obstruents, not relevant here. The variation in measured f_0 due to different estimation algorithms and analysis parameters can be far greater than the 0.5% to 2% error rate arising from mp3 compression.

4. Grabe, Kochanski, and Coleman (2005) also used polynomial equations to describe f_0 in complete intonation phrases, to investigate and compare global properties of statements and questions. The utterances in that study were much shorter, simpler, lab-elicited sentences, for which third-order polynomials were sufficient. Sherr-Ziarko (2019) used 25th-order polynomials (!) to first fit and then segment f_0 contours in long Japanese utterances containing many pitch accents.

5. Not all choices of basis functions support this kind of analytical approach to finding minima and maxima; it is an attractive feature of polynomial modeling that differentiation and root-finding is so easy.

6. For fourth-order polynomials, the transformations are: $c_4 = 8/35\ a_4$; $c_3 = 2/5\ a_3$; $c_2 = \frac{2}{3}\ (a_2 - 30/35\ a_4)$; $c_1 = a_1 + 3/5\ a_3$); $c_0 = a_0 - 3/35\ a_4 + \frac{2}{3}\ (a_2 - 30/35\ a_4)$. See Grabe et al. (2007) appendix C for the transformations required to orthogonalize third-order polynomials. An explanation of the form of such transformations for polynomials of an arbitrary order requires quite a bit of algebra and lies well beyond the scope of this paper and this journal.

7. The notation N(μ, σ) stands for a Gaussian distribution with mean μ and standard deviation σ.

8. All data and code used in this analysis are available at https://osf.io/mus6v/.

9. We obtained many of these films from YouTube, but as they have since been deleted, we cannot provide their URLs here.

References

Allen, Peter S. (1986). Positive aspects of Greek urbanization: The case of Athens by 1980. *Ekistics* 53(318/319):187–94. www.jstor.org/stable/43621978.

Andruski, Jean E., & James Costello. (2004). Using polynomial equations to model pitch contour shape in lexical tones: An example from Green Mong. *Journal of the International Phonetic Association* 34 (2):125–40. doi:10.1017/S0025100304001690.

Arvaniti, Amalia & Mary Baltazani. (2005). Intonational Analysis and Prosodic Annotation of Greek Spoken Corpora. In S.-A. Jun, (ed.), *Prosodic Typology: The Phonology of Intonation and Phrasing*. Oxford: Oxford University Press. 84–117.

Aston, John A.D., Jeng-Min Chiou & Jonathan P. Evans. (2010). Linguistic Pitch Analysis using Functional Principal Component Mixed Effect Models. *Journal of the Royal Statistical Society, Series C (Applied Statistics)* 59:297–317.

Baltazani, Mary & Jun, Sun-Ah. (1999). Topic and focus intonation in Greek. In J. J. Ohala, Y. Hasegawa, M. Ohala, D. Granville & A. C. Bailey (eds.), *Proceedings of the XIVth International Congress of Phonetic Sciences,* 2:1305–08.

Baltazani, Mary, Joanna Przedlacka, & John Coleman. (2020). Intonation of Greek–Turkish contact: a real-time diachronic study. In N. Minematsu (ed.), *Proceedings of the* 10*th International Conference on Speech Prosody* 2020, 730–34, DOI: 10.21437/SpeechProsody. 2020-149.

Barnes, Hilary & Jim Michnowicz. (2015). Broad focus declaratives in Veneto-Spanish bilinguals: Peak alignment and language contact. *Studies in Hispanic and Lusophone Linguistics* 8(1):35–57.

Blanchard, Raoul. (1925). The Exchange of Populations between Greece and Turkey. *Geographical Review* 15(3):449–56.

Boersma, Paul & David Weenink. (2020). Praat: doing phonetics by computer [Computer program]. Version 6.1.16, retrieved June 11, 2020 from http://www.praat.org/.

Bullock, Barbara E. (2009). Prosody in contact in French: A case study from a heritage variety in the USA. *International Journal of Bilingualism* 13(2):165–94. https://doi.org/10.1177/1367006909339817.

Bürkner, Paul-Christian. (2017). brms: An R Package for Bayesian Multilevel Models Using Stan. *Journal of Statistical Software* 80(1):1–28. https://doi.org/10.18637/jss.v080.i01.

Chen, Sin-Horng & Yih-Ru Wang (1990) Vector quantization of pitch information in Mandarin speech. *IEEE Transactions on Communications* 38(9):1317–20. doi: 10.1109/26.61370.

Colantoni, Laura & Jorge Gurlekian. (2004). Convergence and intonation: Historical evidence from Buenos Aires Spanish. *Bilingualism: Language and Cognition* 7(2):107–19.

Eaton, John W., David Bateman, Søren Hauberg, & Rik Wehbring. (2019). *GNU Octave version 5.2.0 manual: a high-level interactive language for numerical computations.* https://www.gnu.org/software/octave/doc/v5.2.0/

Elordieta, Gorka & Nagore Calleja. (2005). Microvariation in Accentual Alignment in Basque Spanish. *Language and Speech* 48(4):397–439. https://doi.org/10.1177/00238309050480040401

Fuchs, Robert & Olga Maxwell. (2016). The effects of mp3 compression on the measurement of fundamental frequency. *Proceedings of Speech Prosody* 2016, Boston.

Gelman, Andrew & Jennifer Hill. (2006). *Data analysis using regression and multilevel/hierarchical models.* Cambridge: Cambridge University Press.

Gizeli, Vika. (1984). *Κοινωνικοί μετασχηματισμοί και προέλευση της κοινωνικής κατοικίας στην Ελλάδα (1920–1930).* [Social transformations and the origin of social housing in Greece (1920-1930).] Athens: Epikairotita.

Grabe, Esther, Greg Kochanski& John Coleman. (2007). Connecting intonation labels to mathematical descriptions of fundamental frequency. *Language and Speech* 50(3):281–310.

Grabe, Esther, Greg Kochanski, and John Coleman. (2005). Quantitative modelling of intonational variation. In *Proceedings of Speech Analysis, Synthesis and Recognition in Technology, Linguistics and Medicine* 2003, Szczyrk, Poland. 45–57. https://ora.ox.ac.uk/objects/uuid:0730281c-dac6-4ec5-a332-22e5cd3cb8b0

Gubian, Michele, Francesco Cangemi & Lou Boves. (2011). Joint Analysis of F0 and Speech Rate with Functional Data Analysis. *International Conference on Acoustics, Speech and Signal Processing* 36. Prague: 4972–75.

Hualde, Jose. (2004). Romance intonation from a comparative and diachronic perspective: possibilities and limitations. In J. Auger, J. C. Clements & B. Vance (eds.), *Contemporary approaches to Romance Linguistics.* Amsterdam: Benjamins. 217–37.

Ipek, Canan & Sun-Ah Jun. (2014). Distinguishing Phrase-Final and Phrase-Medial High Tone on Finally Stressed Words in Turkish. In N. Campbell, D. Gibbon & D. Hirst (eds.), *Proceedings of the 7th Speech Prosody International Conference.* Dublin, Ireland, 393–97.

Janse, Mark. (2009). Greek-Turkish Language Contact in Asia Minor. In T. Tamis (ed.), *Etudes Helleniques: Hellenic Studies* 17(1):37–54.

Janse, Mark. (2015). *Documentation and Description of Cappadocian.* Endangered Languages Archive. http://hdl.handle.net/2196/00-0000-0000-0001-3F8A-0.

Johanson, Lars. (2001). *Discoveries on the Turkic Linguistic Map.* Stockholm: Svenska Forskningsinstitutet i Istanbul.

Kalafati, Fotini. (2018). *Η πολιτική ενσωμάτωση των προσφύγων της Μικρασιατικής καταστροφής στην Ελλάδα κατά τα έτη 1922–1933.* [Political integration of the refugees of the Asia Minor catastrophe in Greece during the years 1922–1933.] MA thesis, University of the Aegean, Greece.

Karatsareas, Petros. (2011). *A study of Cappadocian Greek nominal morphology from a diachronic and dialectological perspective.* Doctoral dissertation, University of Cambridge.

Karlık, Meryem & Azamat Akbarov. (2015). Three Regional Dialects in Turkey. *International Journal of Language and Linguistics* 3(6):436–39. doi: 10.11648/j.ijll.20150306.27

Katsapis, Kostas. (2011). Το προσφυγικό ζήτημα. [The refugee issue.] In A. Liakos & E. Gazi (eds.), *Το 1922 και οι πρόσφυγες, μια νέα ματιά* [1922 and refugees, a new look]. Athens: Nefeli. 125–40.

Kochanski, Greg. (2010). Prosodic peak estimation under segmental perturbations. *Journal of the Acoustical Society of America* 127(2):862–73. doi:10.1121/1.3268511.

Kruskal, William H. & W. Allen Wallis. (1952). Use of ranks in one-criterion variance analysis. *Journal of the American Statistical Association* 47(260):583–621.

Ladd, D. Robert. (2008). *Intonational Phonology.* Cambridge: Cambridge University Press.

Marin, Jean-Michel, Kerrie Mengersen & Christian P. Robert. (2005). Bayesian Modeling and Inference on Mixtures of Distributions. In D. Dey & C. R. Rao (eds.), *Handbook of Statistics* 25: 459–507.

Mennen, Ineke. (2006). Phonetic and phonological influences in non-native intonation: an overview for language teachers. In J. M. Scobbie, I. Mennen & J. Watson (eds.), *QMUC Speech Science Research Centre Working Paper* WP 9. https://eresearch.qmu.ac.uk/bitstream/handle/20.500.12289/151/wp-9.pdf

O'Rourke, Erin. (2012). The realization of contrastive focus in Peruvian Spanish intonation. *Lingua* 122 (5):494–510.

Özge, Umut & Cem Bozsahin. (2010). Intonation in the Grammar of Turkish. *Lingua* 120 (1): 132–75.

Polinsky, Maria. (2018). *Heritage Languages and Their Speakers*. Cambridge: Cambridge University Press.

Queen, Robin. (2012). Turkish-German bilinguals and their intonation: Triangulating evidence about contact induced language change. *Language* 88(4):791–816.

Ramsay, James, Giles Hooker & Spencer Graves. (2009). *Functional data analysis with R and MATLAB*. Springer.

R Core Team (2021). *R: A language and environment for statistical computing.* https://www.R-project.org/.

Ruiter, Laura E. de. (2011). Polynomial Modeling of Child and Adult Intonation in German Spontaneous Speech. *Language and Speech* 54(2):199–223.

Sherr-Ziarko, Ethan. (2019). Prosodic properties of formality in conversational Japanese. *Journal of the International Phonetic Association* 49(3):331–52.

Stan Development Team. (2022a). *RStan: the R interface Stan*, 2.21.5. https://mc-stan.org/

Stan Development Team. (2022b). *Stan Modeling Language Users Guide and Reference Manual*, 2.21.5. https://mc-stan.org

Talkin, David. (1995). A robust algorithm for pitch tracking (RAPT). In W. B. Kleijn & K. K. Palatal (eds.), *Speech Coding and Synthesis*, Elsevier Science B.V. 497–518.

Trudgill, Peter. (2003). Modern Greek dialects. A preliminary classification. *Journal of Greek Linguistics* 4:54–64.

Vasishth, Shravan, & Bruno Nicenboim. (2016). Statistical methods for linguistic research: Foundational ideas–Part I. *Language and Linguistics Compass* 10(8):349–69.

Vasishth, Shravan, Bruno Nicenboim, Mary E. Beckman, Fanfang Li & Eun Jong Kong. (2018). Bayesian data analysis in the phonetic sciences: A tutorial introduction. *Journal of Phonetics* 71:147–61.

Vehtari, Aki, Andrew Gelman & Jonah Gabry. (2017). Practical Bayesian model evaluation using leave-one-out cross-validation and WAIC. *Statistics and Computing*. 27(5):1413–32. doi:10.1007/s11222-016-9696-4. Online, arXiv preprint arXiv:1507.04544.

Venables, William N. and Brian D. Ripley. (2002). *Modern Applied Statistics with S.* 4th ed. New York: Springer.

Zellers, Margaret, Michele Gubian & Brechtje Post. (2010). Redescribing Intonational Categories with Functional Data Analysis. *Proceedings of Interspeech* 2010. https://hdl.handle.net/2066/86541

Appendix A. Sources of audio recordings

The tables below present the distribution of tokens by source. A star next to the token number indicates sources where the speaker's exact age was not known and where their approximate age and classification to one of the four generations was inferred from characteristics of the speaker's appearance in videos or information about their career. As can be seen in the tables below, a number of tokens were extracted from films,[9] after having been judged by a native speaker to be natural-sounding.

Athenian Greek

	Source	Tokens
1	Vocalect (2014 field recordings of natural conversations), http://www.vocalect.eu/?lang=en	346
2	50 Languages.com (sentences recorded in 2000 for a Greek language course), https://www.50languages.com/phrasebook/en/el/	120*
3	Film, Γκολ στον έρωτα (1954)	69
4	Film, Οι παπατζήδες (1954)	18
5	Film, Τζο ο τρομερός (1955)	68
6	Film, Χαρούμενοι αλήτες (1958)	27
7	Film, Νταντά Με Το Ζόρι (1959)	58
8	Film, Η Λίζα τόσκασε (1959)	55
9	Film, Τρεις κούκλες κι εγώ (1960)	67
10	Film, Συνοικία το όνειρο (1961)	18

Asia Minor Greek

	Source	Tokens
1	Bibliothèque nationale de France, Musée de la Parole https://gallica.bnf.fr/ark:/12148/bpt6k129226q/f1.media (Misti, recorded 1927) https://gallica.bnf.fr/ark:/12148/bpt6k129226q/f2.media (Aravisos, recorded 1927)	36
2	Hubert Pernod recordings from the Institut de phonétique (recorded 1930): https://gallica.bnf.fr/ark:/12148/bpt6k10809437?rk=557942;4 https://gallica.bnf.fr/ark:/12148/bpt6k1080939b?rk=472105;2 https://gallica.bnf.fr/ark:/12148/bpt6k1080946g?rk=536483;2 https://gallica.bnf.fr/ark:/12148/bpt6k1080921n?rk=686698;4	73
3	YouTube video of an interview with Despoina Tekelidhou uploaded by Kyriakos Moisidis, 1999 https://www.youtube.com/watch?v=56FYtWDlPhc	6*
4	Unpublished field recordings by Dr. Petros Karatsareas	1035
5	Unpublished field recordings by Dr. Dimitris Papazachariou	215

Turkish

	Source	Number of tokens
1	Aşk Tadında (2009 Turkish Film), https://www.youtube.com/watch?v=_8PUY7er4Dk	6

2	Wilhelm Doegen collection at Humboldt-Universität Lautarchiv https://www.lautarchiv.hu-berlin.de/en/sound-archive/	98
3	50 Languages.com, https://www.50languages.com/phrasebook/tr/en/	144*
4	Aysel Bataklı Damın Kızı (1934 film), https://www.youtube.com/watch?v=2K40V8BqUSQ&ab_channel=BoraBoztekin	29
5	Adnan Menderes'in 53 yıl önceki konuşması (politician speaking), https://www.youtube.com/watch?v=7__cAWUIvBc&ab_channel=etk81	5
6	Atatürk meclis konuşması 1936 (politician speaking), https://www.youtube.com/watch?v=5K0JDH1i-Q&ab_channel=F%C4%B1ratG%C3%B6kdemir	18
7	Atatürk 1932 meclis konuşması, https://www.youtube.com/watch?v=J6unqGMsJDE&ab_channel=%C4%B0%C5%9FteAtat%C3%BCrk	46
8	Atatürk 1937 meclis konuşması, https://www.youtube.com/watch?v=Q8jhs8UKlt8&ab_channel=E%C4%9FitiMedya	24
9	Recording of Hasan Ali Yücel (Turkish Minister of Education) speaking in a meeting in 1939	9
10	Nazım Hikmet (a famous Turkish poet), recorded in a discussion from 1957	8
11	Adnan Menderes 1960, https://www.youtube.com/watch?v=OTqgOUy7evA, https://www.youtube.com/watch?v=46OILoXnwJ4&ab_channel=%C3%9Cst%C3%BCnPALA	3
12	Singer Safiye Ayla speaking on a radio program interview in the 1960s.	23
13	Nazım Hikmet (discussion 1961), https://www.youtube.com/watch?v=48Uk2LAf7Rc&ab_channel=Erc%C3%BCmentG%C3%BCr%C3%A7ay%2FBabil%27denSonra	5
14	Nazım Hikmet (discussion 1962), https://www.youtube.com/watch?v=JwZxPIbram8&t=127s&ab_channel=GunBenderli	12
15	Captain from Black Sea (interview 1970s), https://www.trtarsiv.com/ozel-video/en-yeniler/motorcunun-kaza-anisi-119463	13*
16	Orhan Boran, a comedian (narration 1970s) https://www.youtube.com/watch?v=d_1yTtTq8MM	10
17	İstanbul locals (tv program discussion), https://www.trtarsiv.com/program/meslekler/meslekler-6bolum-124151	40*
18	Atatürk's servant İbrahim Ergüven (interview), https://www.youtube.com/watch?v=—APd9I4iut8&ab_channel=Ge%C3%A7mi%C5%9FteKalanlar	71
19	Singer Safiye Ayla 1970s (interview 1975), https://www.youtube.com/watch?v=EuLuGN-jWXc	30
20	Soldier Sami Yanardağ (interview 1970s), https://www.youtube.com/watch?v=ArrEb6havAM	25
21	Cemal Süreya (interview), https://www.youtube.com/watch?v=VRvnkPd7r-Y&t=143s&ab_channel=Edebiyat-T%C3%BCrk%C3%A7eE%C4%9Fitimi	38
22	Unknown locals (interviews), https://www.youtube.com/watch?v=0BimOp7crNo&ab_channel=TRTAr%C5%9Fiv, https://www.trtarsiv.com/ozel-video/en-yeniler/guzellik-nedir-118060	23*

23	Celal bayar (interviews) 1975 https://www.youtube.com/watch?v=4pmJmEJgen4	8
24	Actor Eşref Kolçak (interview 1978) https://www.instagram.com/p/Bx94TgHgrNd/	2
25	Trabzon actor, https://www.youtube.com/watch?v=KaL587iUZ-I&ab_channel=TRTAr%C5%9Fiv	1
26	Aliye Rona (dialogue), https://www.youtube.com/watch?v=svxZi-7eK3I&ab_channel=SakaliZenci	11
27	Aegean locals (interviews), https://www.youtube.com/watch?v=3z8Q2e8aDGo&ab_channel=TRT%C3%87ATKAPI	6*
28	Lubbey (Aegean) locals (interviews), https://www.youtube.com/watch?v=wISxU4×39zI&ab_channel=ELFATV	3*
29	Psychiatrist on the radio series "Didik Didik Freud" (discussion), https://acikradyo.com.tr/program/44507/kayit-arsivi?date_filter%5Bmin%5D=&date_filter%5Bmax%5D=&sort_by=created&sort_order=DESC&page=0	16
30	Trabzon locals (interviews), https://www.youtube.com/watch?v=eJzrbA5NGVs&ab_channel=TRT%C4%B0zle	12*
31	Nevşehir locals (interviews), https://www.youtube.com/watch?v=yhQY6z7Ajn0, https://www.youtube.com/watch?v=wl2he_yzl60&ab_channel=CTHABERTV	11*
32	Journalists (TV program discussion), https://www.youtube.com/watch?v=CntLT7IIYQg&ab_channel=FOXHaber	10
33	İzmir politician (interview), https://www.youtube.com/watch?v=fOg3fgcDwiU&ab_channel=FOXHaber	14

Appendix B. Independent contributions of the five orthogonal polynomial components

In the section *Modeling f_0 in the Region of Interest* we presented an orthogonal polynomial analysis of prototypical examples of Athenian and Turkish continuation rise contours. Figure 5 showed the contribution of each of the five polynomial terms independently. In order to appreciate the individual contributions of the five components further, Figure B1 shows how the overall polynomial fit in the same two examples is affected when each component is set to zero, one by one. In the Athenian example (Fig. B1, left) setting c_4, c_3, or c_0 to 0 has very little effect on the overall fit (those panels all have a low plateau with a final rise), because those coefficients were close to 0 in any case. Setting c_2 to 0 results in the fit losing its very broad PARABOLA component, so that the fitted contour is now rising rather than gently falling at the start. Since the SLOPE (c_1) component is doing a lot of the heavy lifting in this analysis of the Athenian contour, setting c_1 to 0 results in the fitted curve mostly losing its upward-rising profile at the end.

In the Turkish example (Fig. B1, right), setting the M-OR-W component c_4 to 0 eliminates the two distinct peaks seen in Figure 5. Setting c_3 to 0 eliminates the initial rise, as this WAVE component contributes strongly to the rise-fall-rise contour of the fitted f_0 pattern. In both of these cases, what remains is a falling-rising bowl-like pattern which does not model very well the much more dynamic rise-fall-rise (with final tail-off) of the Turkish pattern. Setting c_2 to 0 results in a fitted curve that does show those two peaks, but now the trough between them is no longer so deep, because of the removal of the PARABOLA component. Setting c_1 to 0 has very little effect on the overall fit as it was close to 0 (-0.07) anyway. Setting c_0 to 0 has no effect at all on the overall shape of the fitted curve, as this is just a constant term; the y-axis scales of the two lower-right panels differ by about 2.4 ($c_0 = 1.6654$), but the shapes are otherwise similar.
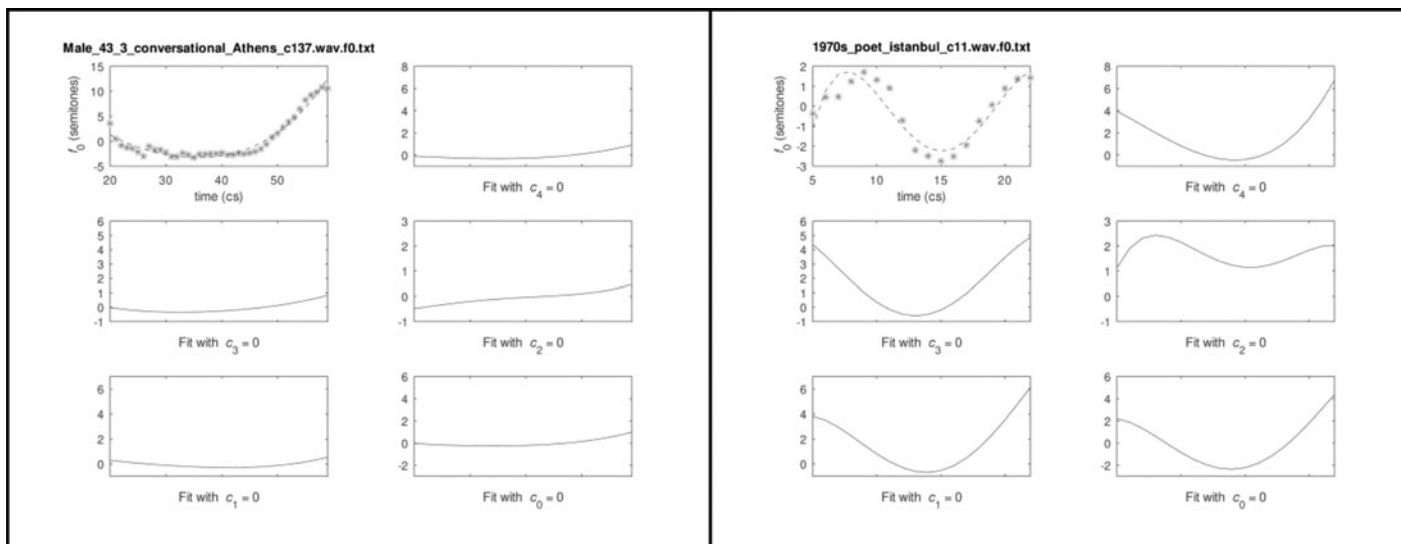
Figure B1. Fourth-order orthogonal polynomial analysis of typical examples of Athenian and Turkish continuation rise contours (top left panels); asterisks: measured f_0, dashed line: fitted polynomial. The effect of setting each component to zero is shown in each of the other five panels, for each of the two examples.

Appendix C. Full model specification for Gaussian mixture models

The Gaussian mixture model was based on the assumption that the distributions of the coefficients c_0 to c_4 as well as τ are a mixture of Turkish-like values and Athenian-like values. As formalized in Table C1, we assumed that for each dependent variable, all Athenian observations y_S for speaker S are normally distributed with a subject-specific mean μ_{A_S} and standard deviation σ_A, and that the subject-specific means μ_{A_S} follow a normal distribution around the grand mean μ_A with standard deviation σ_S (see Table C1 and equation C1). For Turkish, we similarly assumed that each speaker's observations are normally distributed with mean μ_{T_S} and standard deviation σ_T, while subject-specific means μ_{T_S} follow a normal distribution around the grand mean μ_T with standard deviation σ_S.

Table C1. Key assumptions of the Gaussian mixture model of AMG intonation

Athenian	Turkish	AMG
$y_S \sim N(\mu_{A_S}, \sigma_A)$	$y_S \sim N(\mu_{T_S}, \sigma_T)$	$z \sim Bernoulli(\lambda_g)$ $y_S\|z = 0 \sim N(\mu_{T_S}, \sigma_T)$ $y_S\|z = 1 \sim N(\mu_{A_S}, \sigma_A)$
$\mu_{A_S} = \mu_A + \Delta\mu_S$	$\mu_{T_S} = \mu_T + \Delta\mu_S$	$\mu_{A_S} = \mu_A + \Delta\mu_S$ $\mu_{T_S} = \mu_T + \Delta\mu_S$

We further assumed that for each generation g of AMG speakers, each speaker S's observations follow a mixture of the Athenian and Turkish distributions, with λ_g representing the probability of an Athenian-like observation. This amounts to assuming that each AMG speaker of generation g is capable of producing Athenian-like utterances with probability λ_g and Turkish-like utterances with probability $1 - \lambda_g$. We further assumed that the subject-specific deviation from the grand mean of the dialect (Turkish and Athenian) is the same for both dialects among AMG speakers.

$$\Delta\mu_S \sim N(0, \sigma_S) \tag{C1}$$

We assumed that λ_g was affected by generation in the way specified in equation C2. We used successive differences contrasts (e.g., Venables & Ripley, 2002) $G_{(2-1)}$, $G_{(3-2)}$, $G_{(4-3)}$ for the factor *generation* such that a_λ has an interpretation as the average log-odds of producing an Athenian-like utterance across all generations, while $b_{\lambda,(2-1)}$, $b_{\lambda,(3-2)}$, $b_{\lambda,(4-3)}$ represent successive differences in the log-odds of an Athenian-like utterance between generations 2 and 1, 3 and 2, and 4 and 3. Table C2 shows the successive differences contrasts for generation.

$$\text{logit}(\lambda_g) = a_\lambda + b_{\lambda,(2-1)} \cdot G_{(2-1)} + b_{\lambda,(3-2)} \cdot G_{(3-2)} + b_{\lambda,(4-3)} \cdot G_{(4-3)} \tag{C2}$$

Table C2. Successive differences contrast matrix for generation

Generation	$G_{(2-1)}$	$G_{(3-2)}$	$G_{(4-3)}$
Generation 1	−1/4	−2/4	−1/4
Generation 2	1/4	−2/4	−1/4
Generation 3	1/4	2/4	−1/4
Generation 4	1/4	2/4	3/4

All parameters were given weakly informative prior distributions. The same priors were used for all dependent variables. Tables C3 and C4 list the priors for all parameters in the model.

Table C3. *Prior distributions for all model parameters except σ_S.*

Parameter	Prior Distribution
μ_A, μ_T	*Normal*(0, 5)
σ_A, σ_T	*Half-Normal*(1, 5)
$a_\lambda, b_{\lambda,1}, b_{\lambda,2}, b_{\lambda,3}$	*Normal*(0, 2)

Table C4. Prior distributions for model parameter σ_S.

Parameter	Prior, c_1-c_4	Prior, τ
σ_S	Student-t(3, 0, 2.5)	Student-t(3, 0, 22.1)

Appendix D. Full model specification for linear mixed-effects models

The baseline linear mixed-effects models for all dependent variables included fixed effects for generation, dialect, as well as their interaction, and by-speaker intercept as stated in the brms model formula in D1. Generation and dialect were represented using successive differences contrast matrices given in Tables C2 and D1 (e.g., Venables & Ripley, 2002). Tables D2 and D3 list the prior distributions for the fixed effects and random effects of the model respectively.

$$y \sim 1 + (G_{(2-1)} + G_{(3-2)} + G_{(4-3)}) * (D_{(AMG-Ath.)} + D_{(Tur-AMG)}) + (1|participant) \tag{D1}$$

Table D1. Successive differences contrast matrix for dialect

	$D_{(AMG-Ath.)}$	$D_{(T-AMG)}$
Athenian	$-2/3$	$-1/3$
Turkish	$1/3$	$-1/3$
AMG	$1/3$	$2/3$

Table D2. Prior distributions for all model parameters except σ_S.

Parameter	Prior Distribution
Intercept	*Normal*(0, 5)
Slopes	*Normal*(0, 5)
σ	*Half-Normal*(1, 5)

Table D3. Prior distributions for model parameter σ_S.

Parameter	Prior, c_1-c_4	Prior, τ
σ_S	Student-t(3, 0, 2.5)	Student-t(3, 0, 22.1)