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12.740 Paleoceanography
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PALEO-ECOLOGICAL TEMPERATURE ESTIMATES

- I. Paleo-ecological temperature estimation is based on the empirical observation that certain species of marine organisms leave fossils on the seafloor that correspond to temperature patterns in oceanic surface waters. Downcore records seem to correspond to the known glacial/interglacial fluctuations.

Image removed due to copyright considerations.

Source: A. Bé. figure 6.6.

- A. Although this correlation has been known for some time, in the early days there was uncertainty regarding the optimal way to use and interpret this data. Ericson and coworkers at Lamont focussed on developing quick methods for stratigraphy based on a small number of marker species (e.g. *G. menardii*). This method is still useful for developing a preliminary stratigraphy. Unfortunately, this method provided misleading climatological information and led to a conflict between Ericson and Emiliani. Later, Lidz (1966) showed that complete counts of foraminiferal species provided more information which was consistent with the oxygen isotope record of glacial/interglacial transitions .

Image removed due to copyright considerations.

Source: Imbrie and Imbrie (1979) *Ice Ages: Solving the Mystery*, figure 33.

II. Imbrie-Kipp method: factor analysis and transfer functions.

- A. This method assumes that there are certain groupings of species (assemblages) which can be identified by linear multivariate statistics: orthogonal Q-mode factor analysis, and which remain coherent over time. It also assumes that correlations (of at least some of these groupings) maintain consistent relationships with environmental properties (e.g. surface temperature).
- B. In an oversimplified form, the assemblages can be viewed of as grouping of species. Suppose you have three species, and three groupings:

<u>Species 3</u>		Species 1	Species 2
1	Group 1	7	2
3	Group 2	4	3
6	Group 3	2	2

Then each sample would be decomposed into linear combinations of groups 1, 2, and 3. This obviously has little advantage unless the three groupings follow the environmental factors better than the individual species. However, if 33 species of foraminifera can be reduced to 6 groupings, a significant simplification has been achieved. But how should you group the species data? Imbrie's answer was to use linear statistical analysis.

See: Fundamentals of Factor Analysis

i.e.

$$U_{57,3} = B_{57,1}F_{1,3} + B_{57,2}F_{2,3} + B_{57,3}F_{3,3} + \dots$$

|
 % species 3 in
 sample 57

|
 loading of factor
 2 for sample 57

|
 contribution of
 species 3 to factor 3

where

N is of the order of 50-1000.

n is of the order of 30-100.

m is of the order of 5-10.

This equation describes each of the very large number of samples for which a large number of species has been counted as the linear combination of a small number of a small number of assemblages.

D. Then, to interpret paleo-data, it is assumed that the assemblages remain stable, so that we can then interpret downcore data as linear combinations of those same assemblages:

$$B = U F^T$$

transpose of F
 determined from
 core-top study

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i.e.:

$$B_{57,4} = U_{57,1}F_{1,4}^{T} + U_{57,2}F_{2,4}^{T} + U_{57,3}F_{3,4}^{T} + \dots$$

|
loading of factor
4 on sample 57

|
% species 1
in sample 57

|
contribution of species 2
to factor 4

e.g. (Kipp, 1976, p. 23)

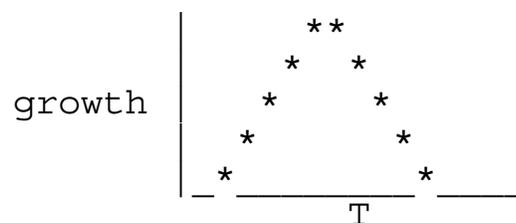
	Trop	Sub-trop	Transit.	Subpolar	Polar	Margin
<u>N. pachyderma</u> (left)	-0.018	0.016	-0.029	-0.027	0.987	0.011
<u>G. ruber</u> (white)	0.922	0.112	-0.013	-0.054	0.030	-0.098

Gyre

E. However, algebraically, there are an infinite number of ways to decompose the core top data so that it satisfies these equations. Varimax Q-mode factor analysis is an objective method for finding one of these solutions, given a choice of the number of factors to be used. The number of factors is arbitrary, however!.

G. Map assemblages. Can be used to find out how many factors are reasonable (i.e., factors that are 'unmappable' are considered to be in the noise).

1. Paleo-ecological assumption:



i.e. $T_i = f[B_{CT}(i,j)]$

1. Abstract - discuss
2. Rejection of samples - objectivity
3. "Summer" "Winter" definitions (cold/warm season) summer/winter T maps mean? Is a "seasonality" What do available in this data?
4. Effect of differential dissolution
5. Effect of transport by currents, etc.
6. What is the "Gyre margin" assemblage?
7. *G. sacculifer*, *duertrei*, *menardii*: Gulf Stream indicators?
8. Comparison with plankton- tow observations
9. Problem of very cold temperatures: below about 8°C, foraminiferal assemblages are monospecific.
10. Species maps - how good is the T-correlation?

Images removed due to copyright considerations.

11. "Factor" distributions

Images removed due to copyright considerations.

12. Differences map

III. Initial results from the Imbrie-Kipp technique: CLIMAP project

A. Global Ocean Temperature Reconstructions during the last Glacial Maximum

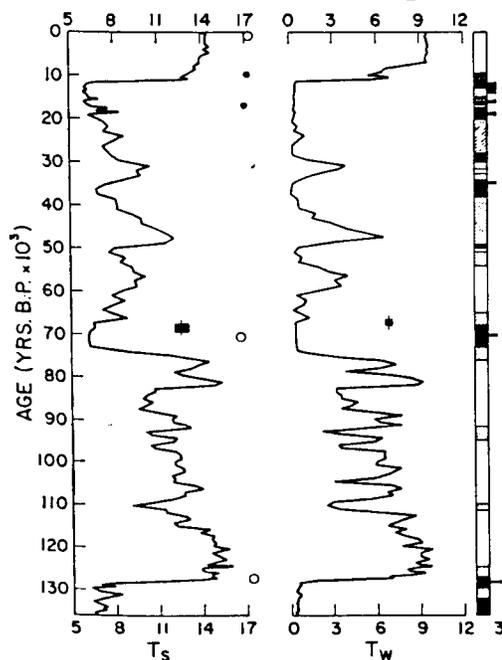
1. Largest change is in the temperatures of the North Atlantic Ocean polewards of 40°N: >10°C cooling over a large area.
2. Tropical sea surface temperatures are surprisingly stable: change is less than 2°C over large areas of the tropics. This result fits in well with the Shackleton/Dansgaard revision of the interpretation of foraminiferal $\delta^{18}\text{O}$.

Image removed due to copyright considerations.

3. Other than the North Atlantic, polar waters expanded about 5° (latitude) equatorward.
4. Some evidence of cooler temperatures in wind-driven upwelling environments (especially off Northwest Africa, but perhaps also on other eastern boundaries and on the equator).

B. Downcore records of paleotemperature variability during the last 150,000 years.

1. Northern North Atlantic temperature variability: looks similar to $\delta^{18}\text{O}$ variability.



Faunal indices T_s , T_w , and S vs age in North Atlantic core V23-82. Age is determined by Model 1 (see text and Table 3). Solid circles indicate ^{14}C -dated samples; open circles indicate stratigraphic dates. Thick bars indicate 80% confidence intervals for analytical precision of indices. Horizontal lines indicate samples lacking coccoliths (McIntyre *et al.*, 1972). Pattern in column indicates samples with high mineral detritus content in the $>149 \mu\text{m}$ fraction; diagonal pattern 10–20% of sample, solid pattern $>20\%$ of sample.

source: Sancetta *et al.*, 1973

IV. Critique of the Imbrie-Kipp method

- A. The Imbrie-Kipp method (and all other methods that require completely empirical calibration) explicitly assumes that the temperature responses of the assemblages remains constant through time. But what happens during genetic evolutionary change? Can species evolve their temperature tolerance in the face of environment pressure?
1. This kind of problem is most serious in continental environments where species may not be very mobile; e.g., even if the environment changes, in the short term there may not be any "seed corn" to allow the optimum assemblage to develop, so a non-optimum species has some time in which to respond to evolutionary pressures before more efficient competitors arrive.
 2. In marine environments, this problem is mitigated by the great mobility of the species; it is generally very easy for species to migrate (but remember that in the case of foraminifera, "migration" occurs via ocean currents and eddies) as the temperature bands move.
 - a. This is not always true however. How can cold north polar and south polar species intermix? (Perhaps by subsurface exchange, although this may be difficult.)
 - b. One counter-example of this rule is the disappearance of pink-pigmented G. ruber 120,000 years ago in the Pacific and Indian Oceans. This species existed in all of the oceans before that time, and is still quite abundant in the Atlantic Ocean. There is nothing obvious about the environmental differences between the oceans that could account for the non-occurrence of this species, so it appears that simply there is no "seed corn" for this species in the Pacific and Indian Oceans. Migration of this species from the Atlantic is prevented by the hostile environment (e.g. cold) of the circumpolar connection between the oceans.
 - i. This might even be an example of a time-transgressive extinction in the making....
 3. Even in marine environments, this problem is very serious for very old environments because of the extinction of species; samples that are (say) about 50 million years old have none of the same species that exist today. How can you calibrate a species that doesn't exist in the modern ocean?
 - a. For foraminifera, this problem becomes significant at about 1-3 million years ago.
- B. The Imbrie method has some significant advantages: it is objective and the orthogonality of the factors allows one (at least in principle, if not always in practice) to "throw away" information that is not relevant to reconstructions of the particular property that we are interested in (e.g., if some factors respond to salinity or some other variable rather than temperature, we can leave them out of the paleotemperature regression (e.g., the "gyre margin" assemblage). But it also has some disadvantages: the regression equations have completely arbitrary form: they have no basis in theory.

Since the equations are chosen to fit the data, they are OK for samples that lie within the range of the calibration samples. But for samples that lie outside of the calibration range, the equations are unconstrained and can blow up: **the "no-analogue" problem**

1. One of the solutions to this problem is to avoid using the technique for samples that fall outside the calibration range of factor compositions. Unfortunately, this includes some interesting areas, and it also has a somewhat arbitrary nature: how does one assess exactly when the no-analogue problem arises?
- C. The method also has some problems with dissolution of calcium carbonate on the seafloor: some species of foraminifera are more sensitive to dissolution than others, so dissolution can alter the species composition and hence the factor composition.
1. One way to minimize the problem is to include "dissolved" samples in the set of calibration samples. This was done by Kipp (1976) in her Atlantic transfer function. It does not work as well in the Pacific however, where the extent of dissolution is greater; much of the micropaleontological information has been lost.
- D. A more troublesome aspect of the regression procedure is the arbitrary nature of the calibration data (e.g., sea surface temperature, SST). One can also do a calibration to "temperature at 100m depth" or "temperature at 200m depth"; these work almost as well (as judged by the standard deviation of the fits), mainly because SST is highly correlated with subsurface temperatures. Also, since temperature has a seasonal cycle, one can get equations for "winter temperature", "summer temperature", or "annual average temperature"; again, these all work just about as well. One could also regress against "sea-surface salinity" (SSS) or "productivity"; these don't work as well, but they do give calibrations that are better than random. But SST is highly correlated with SSS; what is it that foraminifera are really measuring?
1. I recommend that you look at these regressions in this way: in effect we are trying to put a number that everybody can understand (e.g. SST) onto data that only micropaleontologists or mathematicians understand (e.g. species composition of a fossil sample, or factor loadings). The idea is valid only to the extent that the variable you are assigning to the data is in reality a master variable controlling the formation of a fossil assemblage. There is good reason (i.e., maps of global foraminiferal distributions) to believe that foraminiferal species composition is highly correlated with SST (and subsurface temperatures which must be highly correlated with SST). So it is reasonable to derive temperatures from foram species data. It is not so clear whether we should make the correlation to winter SST, summer SST, or any closely-correlated variant of this theme. Since paleoenvironmental models (e.g. General Circulation Models (GCM) of the atmosphere) need to have seasonal SST information to operate, it is reasonable to make the regressions for each season so as to provide the necessary information to make the model operate properly.
 2. It is probably not reasonable to take the winter/summer estimates seriously. Relenting a little from this skeptical attitude, we should acknowledge that there are

many species and several factor analysis assemblages in that sample, and these may contain information on the separate seasons. But it is not clear that a simple assemblage regression against winter or summer SST is a valid way to get at this information.

3. It is certainly not reasonable to take the paleosalinity estimates seriously. SST and SSS are too highly correlated, so if T is the dominant variable, then the regressions simply tend to give us the modern T-S correlation. The mean salinity of the ocean was 1‰ higher during the last ice age; did this have any effect on the species composition of warm tropical waters?
 - a. However, it is not entirely unreasonable that salinity variations play some role in the growth of foraminifera. For example, few foraminifera grow in the most saline waters of the Red Sea ($S > 40‰$). Some species of foraminifera probably can't tolerate very low salinities. So there is probably some paleosalinity information when near the tolerance limits of foraminifera. How do we use this information however, and what is its margin of error?

V. One alternative to Imbrie-Kipp: **Modern Analogue Technique (MAT)**

- A. As suggested in section IV.D.1. above, in trying to assign a paleotemperature to a fossil assemblage from a sediment core, in effect we are trying to find a modern sample of approximately the same species composition and saying that the temperature above that modern site is the paleotemperature of the ancient site at the time the fossil assemblage formed. MAT proposes to do this comparison explicitly; e.g. it takes the species composition of the fossil sample, and assigns the it the temperature associated with the most similar modern samples.
 1. There are many ways this might be done - how do we assess the level of similarity between two samples? The form of MAT adopted for oceanic samples uses a simple and easy-to-understand method. Consider the n-dimensional space represented by the percentage of each species as an independent dimension. Samples are considered the most similar when the the distance between them is the smallest. So the paleotemperature estimate adopted is the average of the temperatures of the core-top samples closest to the paleo-sample in species space.
 2. One of the advantages of this approach is that it provides a quantitative measure of the degree to which you are able to find a suitable analogue. You are always able to find the most similar modern samples, and hence derive a paleotemperature estimate, but you also get a dissimilarity coefficient that can tip you off when the modern and ancient samples are really not all that similar.
 3. Work by Bob Thunell in western tropical Pacific suggests that MAT works better than Imbrie-Kipp in samples that are relatively heavily dissolved. MAT simply finds a modern heavily-dissolved analogue sample, whereas Imbrie-Kipp struggles to keep the species assemblage groupings constant. similar.
 4. The LGM temperatures of the Atlantic Ocean recently were mapped out using a

MAT variant by Pflaumann et al. (2003). Note: discuss distance-weighting of SST estimate.

VI. One of the major current paleoclimatic conundrums: Imbrie-Kipp and planktonic oxygen isotope evidence suggest that tropical sea-surface temperatures were not changed much during the last glacial maximum. But high-elevation evidence from continental environments and islands suggest that the tropics cooled considerably: snow lines on tropical mountains were lower, and the vegetation in the tropical mountains indicate a cooler climate. These lines of evidence (and others which have appeared more recently) appear to suggest tropical sea surface cooling where CLIMAP suggests little change. What's the problem?

similar.

A. One possible “clue” to this problem was provided by Prell et al. (1976), who did separate factor analyses on core tops and LGM samples and found that the LGM samples yielded one more factor than the core top samples. They dubbed this factor the “glacial cool equatorial” factor.

similar.

B. Much later, after being forced to reassess the problem of tropical sea surface temperatures, Hostetler and Mix (1999) performed factor analyses on downcore samples from the tropics, on the assumption that the modern core top miss out on a significant factor. Using the factors derived from this downcore factor analysis, they devised a paleotemperature transfer function by regressing modern SST vs. these factors. Then they used this new transfer function to estimate tropical LGM SSTs – and they found much cooler LGM SST estimates.

Image removed due to copyright considerations.

Please see:

Figure 1 in Hostetler and Mix. *Nature* 399 (June 17, 1999): 674.

C. The SST of the LGM ocean is being remapped by the EPILOG program (Mix et al., 2001) based on this knowledge and other types of paleo-temperature tracers.

Not everyone is entirely happy with this resolution of the problem; it's a sort of "closing the barn after the horse has left" solution (or perhaps a "tell us what the answer is and we will figure out a way to get the forams to get that answer" solution!

We will return to this problem later.

Readings:

Read the * items to glean the essence of what they are trying to accomplish - they should not be considered the final word in Y2K!

- *1. Imbrie, J. and N.G. Kipp (1971) A new micropaleontological method for quantitative paleoclimatology, in Late Cenozoic Glacial Ages (ed. K.K. Turekian), Yale Univ. Press, New Haven, pp. 71-182.
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- 3. Overpeck, J.T., T. Webb II, and I.C. Prentice (1985) Quantitative interpretation of fossil pollen spectra: dissimilarity coefficients and the method of modern analogs, *Quat Res.* 12: 47-82.
- 4. Anderson D. M., Prell W. L. ,and Barratt N. J. (1989) Estimates of sea surface temperature in the Coral Sea at the last glacial maximum. *Paleoceanogr.* **4**, 615-627.
- 5. Joreskog, Klován, and Reymont (1976) Geological Factor Analysis, Elsevier, Amsterdam, 1976, 178 p.
- 6. Hostetler, S. W. and A. C. Mix (1999). "Reassessment of ice-age cooling of the tropical ocean and atmosphere." *Nature* 399: 673-676.
- 7. Lidz L. (1966) Deep-sea Pleistocene Biostratigraphy. *Science.* **154**, 1448-1452.
- 8. Mix, A. C., E. Bard, et al. (2001). "Environmental Processes of the Ice Age: Land,

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9. Mix, A. C., E. Bard, et al. (2001). "Environmental Processes of the Ice Age: Land, Oceans, Glaciers (EPILOG)." *Quat. Sci. Rev.* 20: 620-657.
 10. Pflaumann, U., M. Sarnthein, et al. (2003). "Glacial North Atlantic: Sea-surface conditions reconstructed by GLAMAP 2000." *Paleoceanogr.* 18: 1065, doi:10.1029/2002PA000774.
 11. Prell, W. L., J. V. Gardner, et al. (1976). Equatorial Atlantic and Caribbean foraminiferal assemblages, temperatures, and circulation: Interglacial and glacial comparisons. *Investigation of Late Quaternary Paleoceanography and Paleoclimatology* Geol. Soc. Am. Memoir. R. M. Cline and J. D. Hays. Boulder, CO USA, Geo. Soc. Am. 145.