Empirical modeling the stock fluctuations of sardine in the Japan/East Sea

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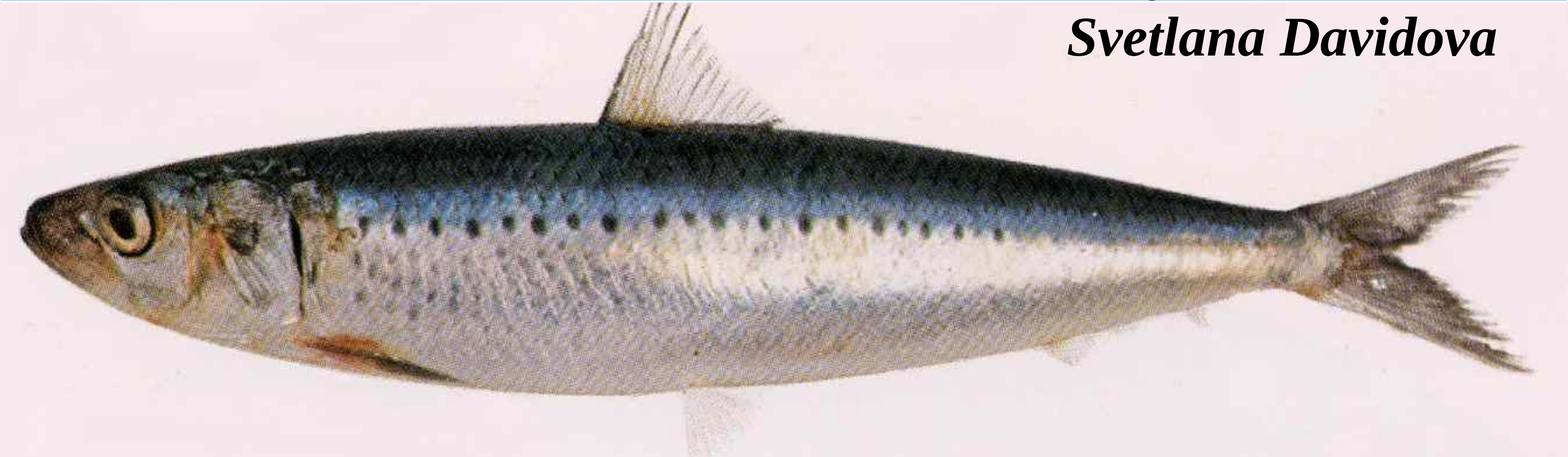
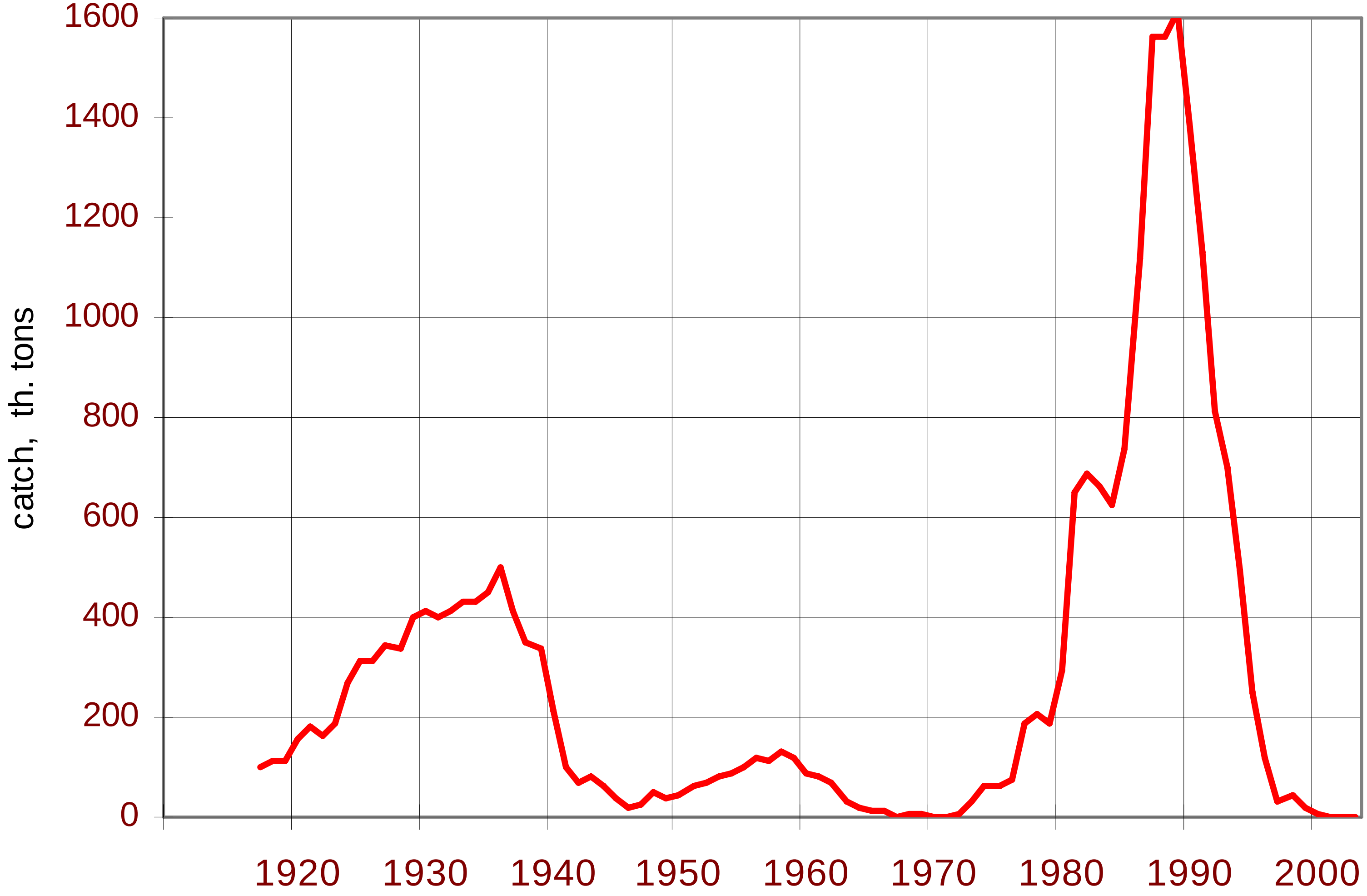


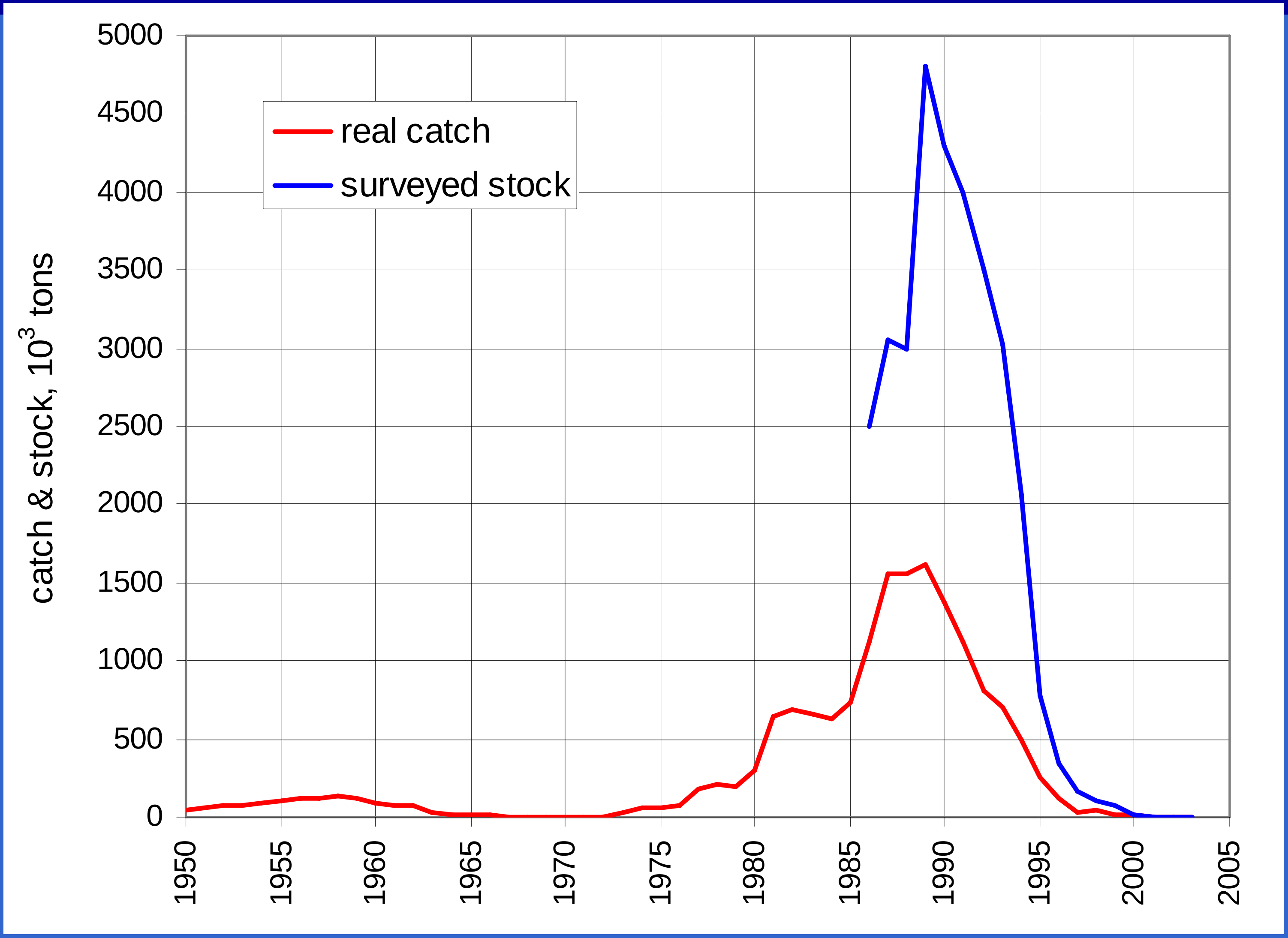
Goals:

1. To create an empirical model suitable for the stock and catch forecasting
2. To estimate the main factors responsible for the stock fluctuations

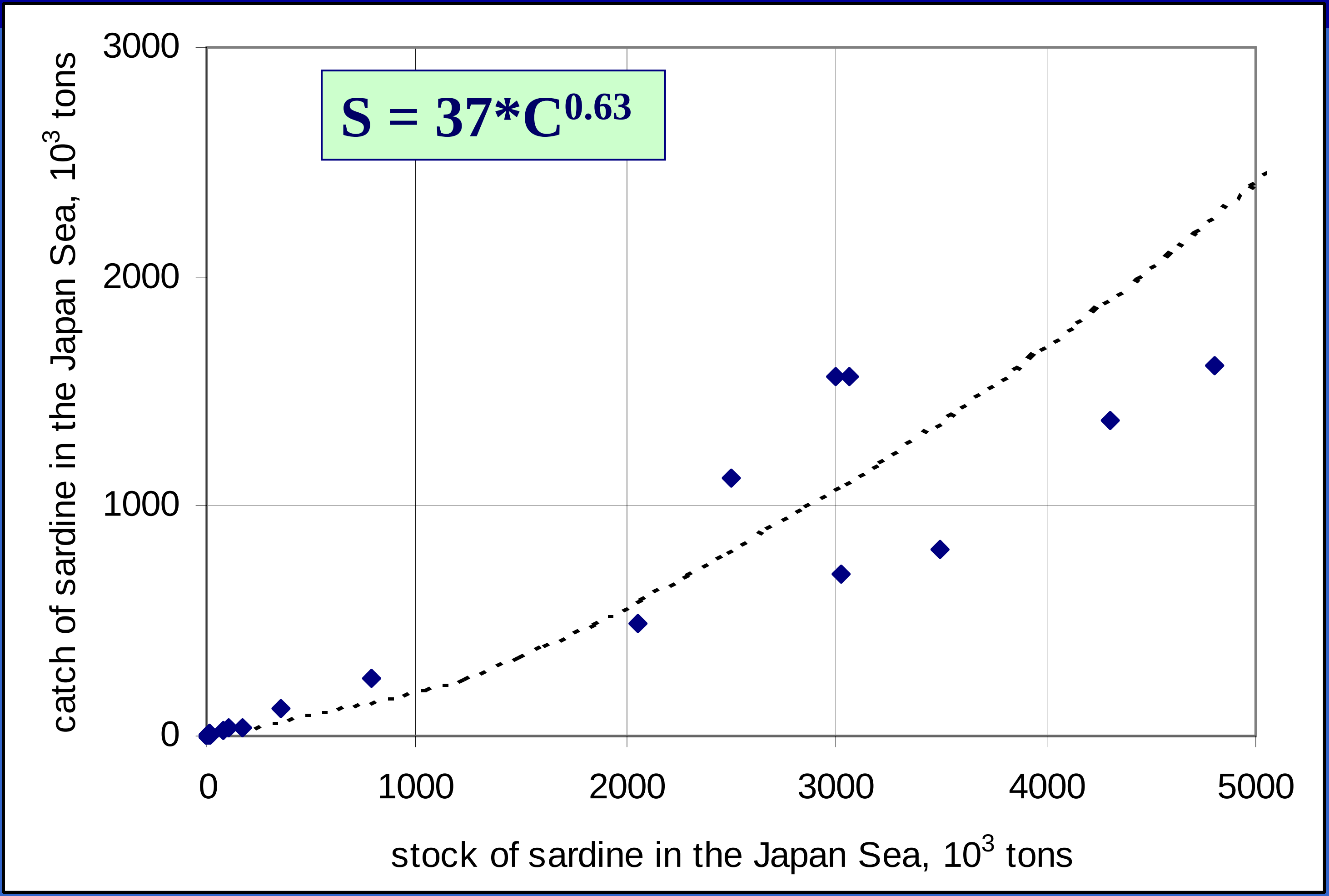
Total catch of sardine in the Japan/East Sea



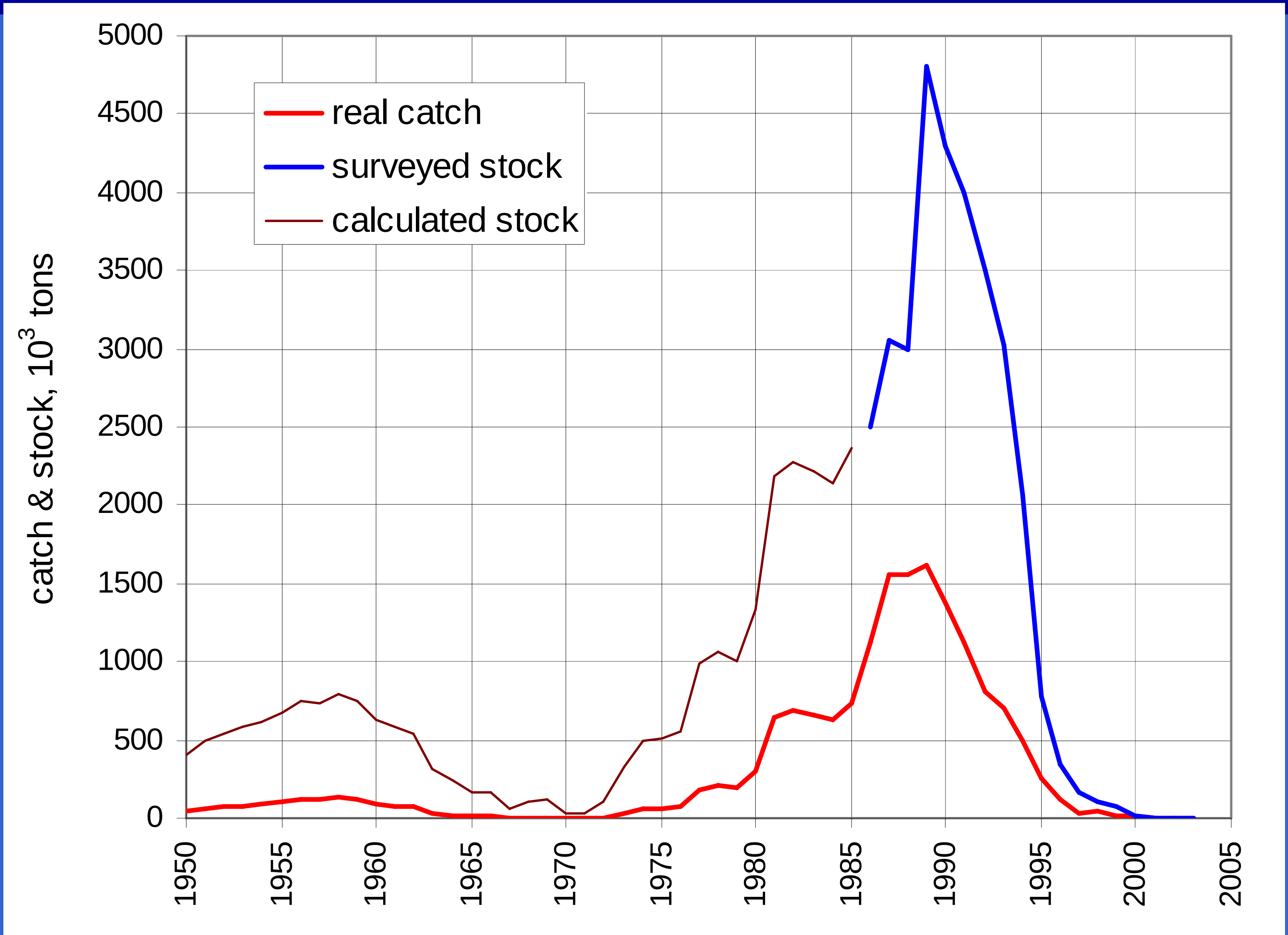
Spawning stock of sardine in the Japanese EEZ surveyed since 1986 has similar fluctuations



However, the regression between catch and spawning stock is not linear



The approximation $S = 37\ C^{0.63}$ was used for calculation the stock in the years before 1986 from the data on catch



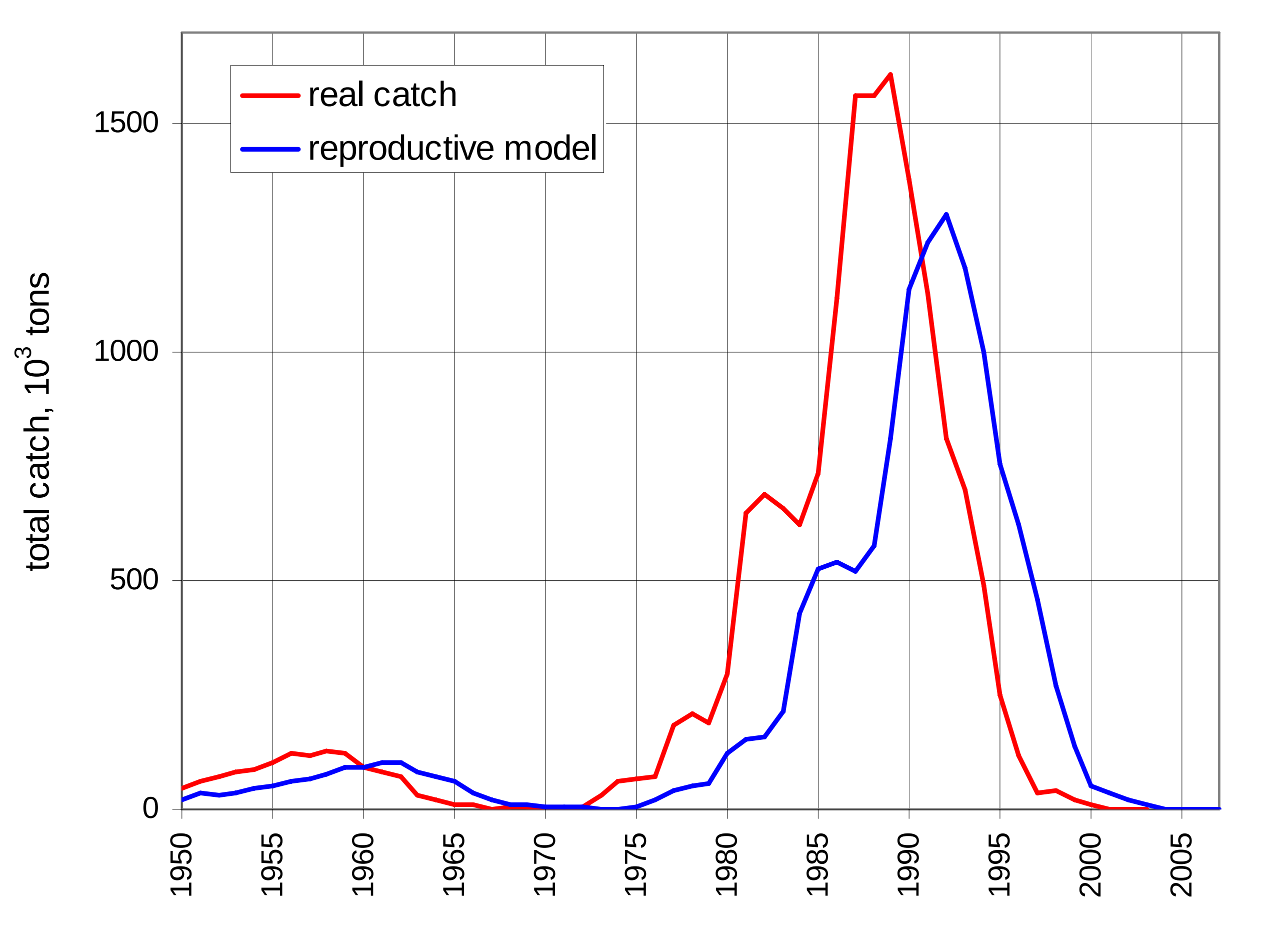
Simple reproductive model with constant fecundity f and mortality m

$$S_j = \Sigma_{i=3,4,5,6} [S_{j-i} * f * (1-m)^i]$$

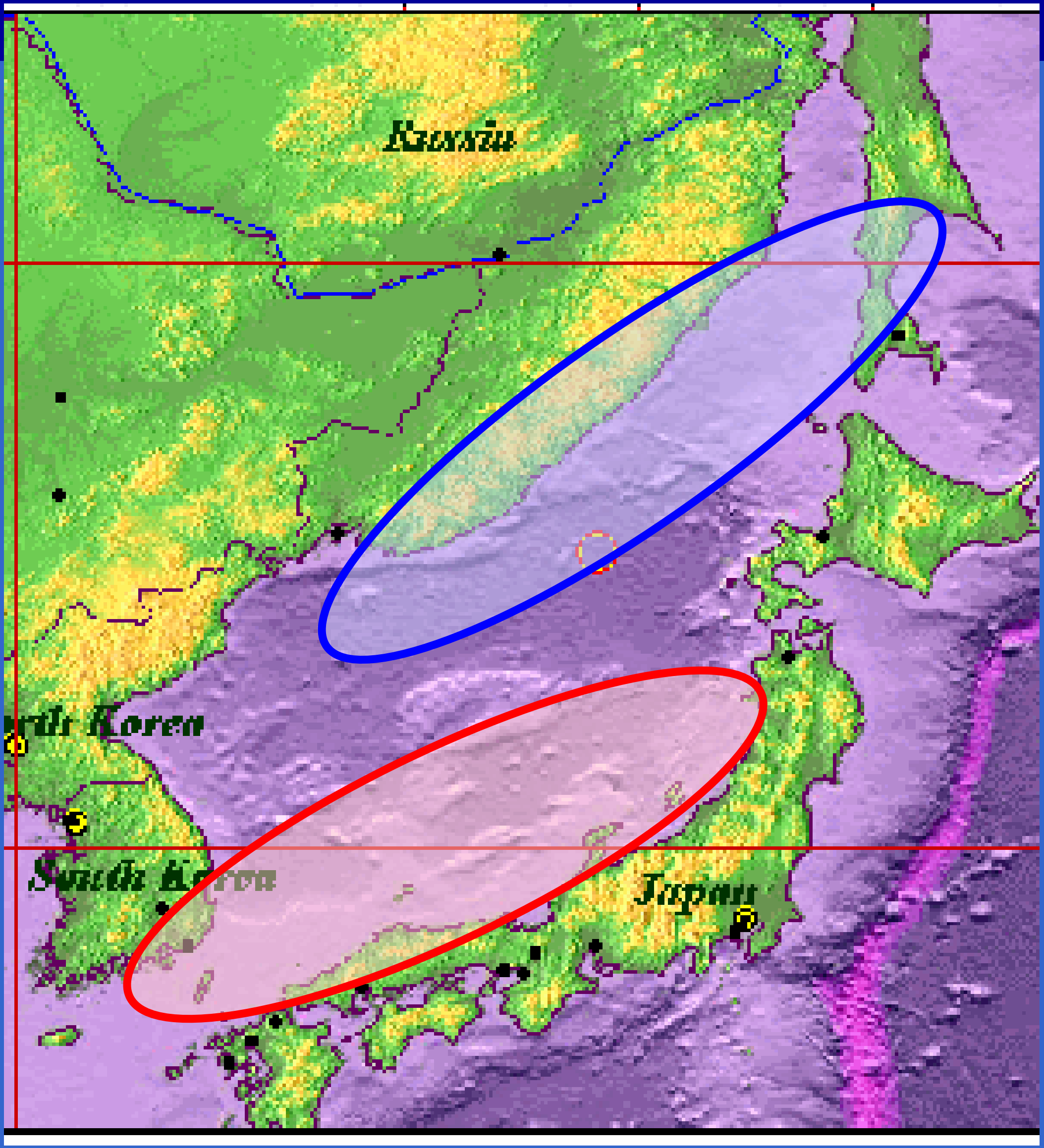
R=0.70

The model determines only 50% of the catch variance and is not suitable for the forecasting.

We suppose that the model should be enhanced by taking into account environmental factors



We suppose that environmental conditions both on spawning grounds and feeding grounds are important



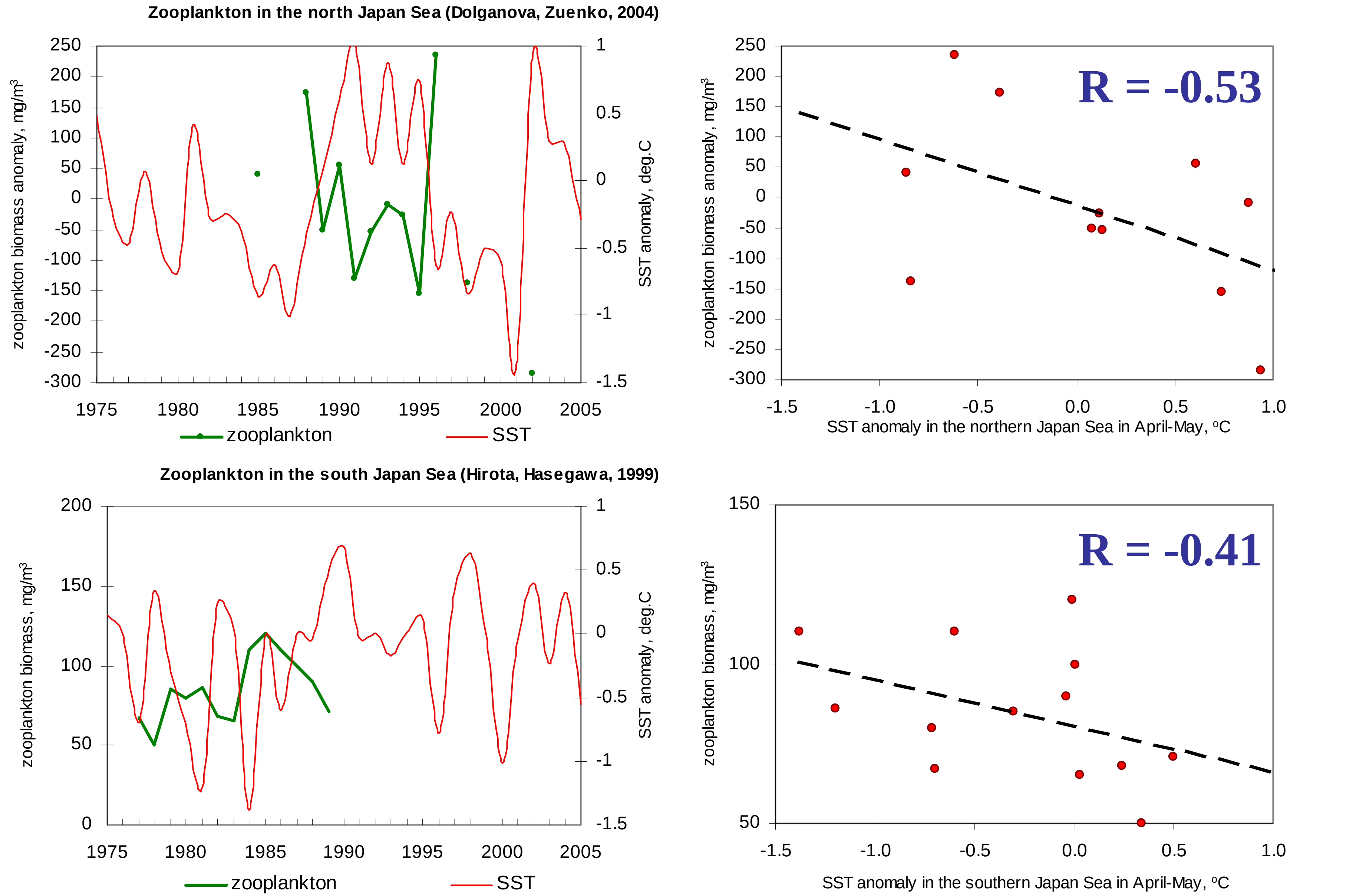
Sardine spawn in the southern part of the Sea.
Larvae feed in the same area, but adults – mostly in the northern part of the Sea.

Hypothesis: number of each generation depends both on number of eggs and their survival

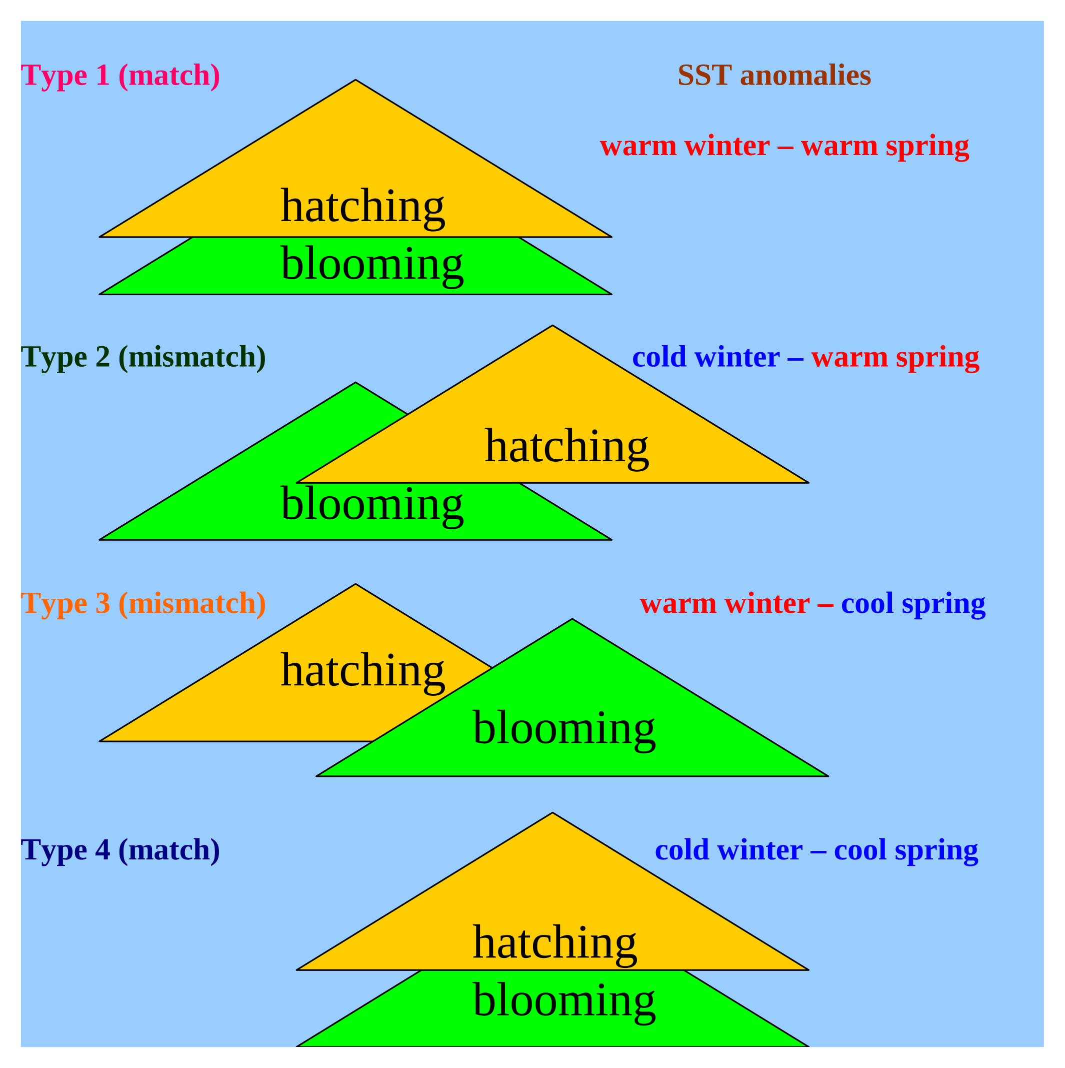
Possible environmental factors influencing on the eggs and larvae survival are:

-thermal conditions on spawning grounds in winter (for eggs);
-feeding conditions on spawning grounds in spring (for larvae);
-feeding conditions on feeding grounds in previous year (for pre-spawning adults)

Plankton abundance depends generally on SST in spring



From the other hand, sufficient feeding of larvae depends on the match of its hatching with plankton bloom (Cushing match/mismatch hypothesis)



Accordingly with the times of hatching and blooming, four variants of match/mismatch are possible:

Thus, abundance of each generation can be influenced by:

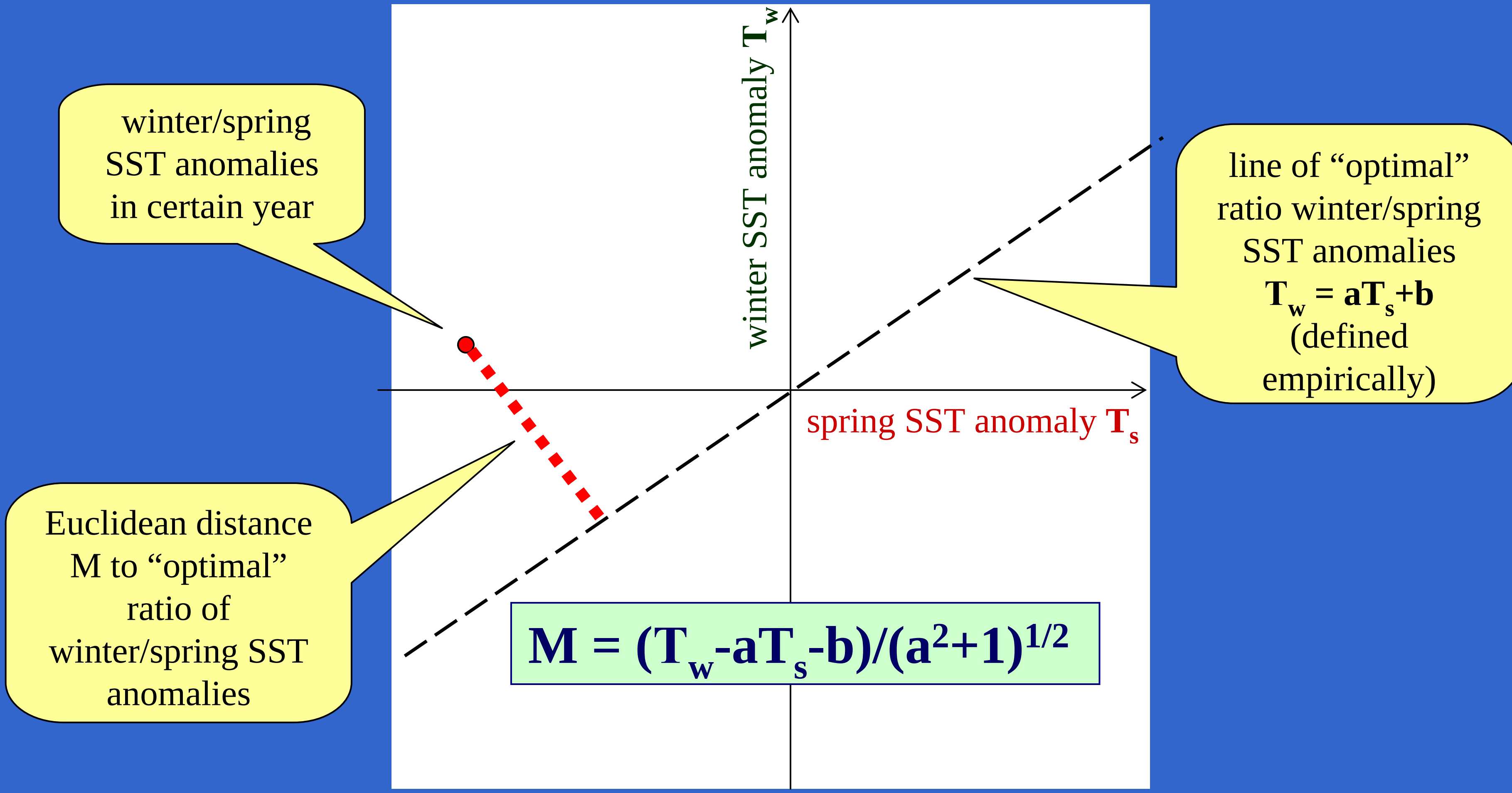
- number of parents $(S_{spawning})$
- age (adults mortality is supposed here as low and constant) (i)
- natural potential fecundity of the species (f) that is corrected by:
    - thermal conditions on feeding grounds in previous year (T_N)
    - thermal conditions on spawning grounds in winter (T_W)
    - thermal conditions on spawning grounds in spring (T_S)
    - match of hatching with blooming (M)
    - density of spawners

or

$$\boxed{S_j = S_{parents} * (f + k_N T_N + k_W T_W + k_S T_S + k_M M + k_D S_{parents}) * (1-m)^i}$$

where k_N, k_W, k_S, k_M, k_D – are coefficients

How to estimate the value of “match”?



Extent of match is estimated quantitatively as Euclidean distance on the diagram “winter SST anomalies – spring SST anomalies” from the point of real winter/spring SST anomalies to the line of their “optimal” ratio, which has to be defined from empirical data

Spawning stock of sardine is formed by generations 3+ (partially), 4+, 5+, and 6+

Thus, the spawning stock in the year j is:

$$\mathbf{S_j = \Sigma_{i=3,4,5,6} \left[K * S_{j-i} * (f + k_N T_{N(j-i-1)} + k_W T_{W(j-i)} + k_S T_{S(j-i)} + \right.}$$

$$\mathbf{\left. + k_M M_{(j-i)} + k_D S_{j-i}) * (1-m)^i \right]}$$

$K = 1$ for the ages 4+, 5+, 6+; $K < 1$ for the age 3+

The same stock is exploited by fishery

This multiple regression model differs from simple reproduction model by strong dependence on environmental factors

Averaged JMA data on SST were used as parameters T_N, T_W, and T_S

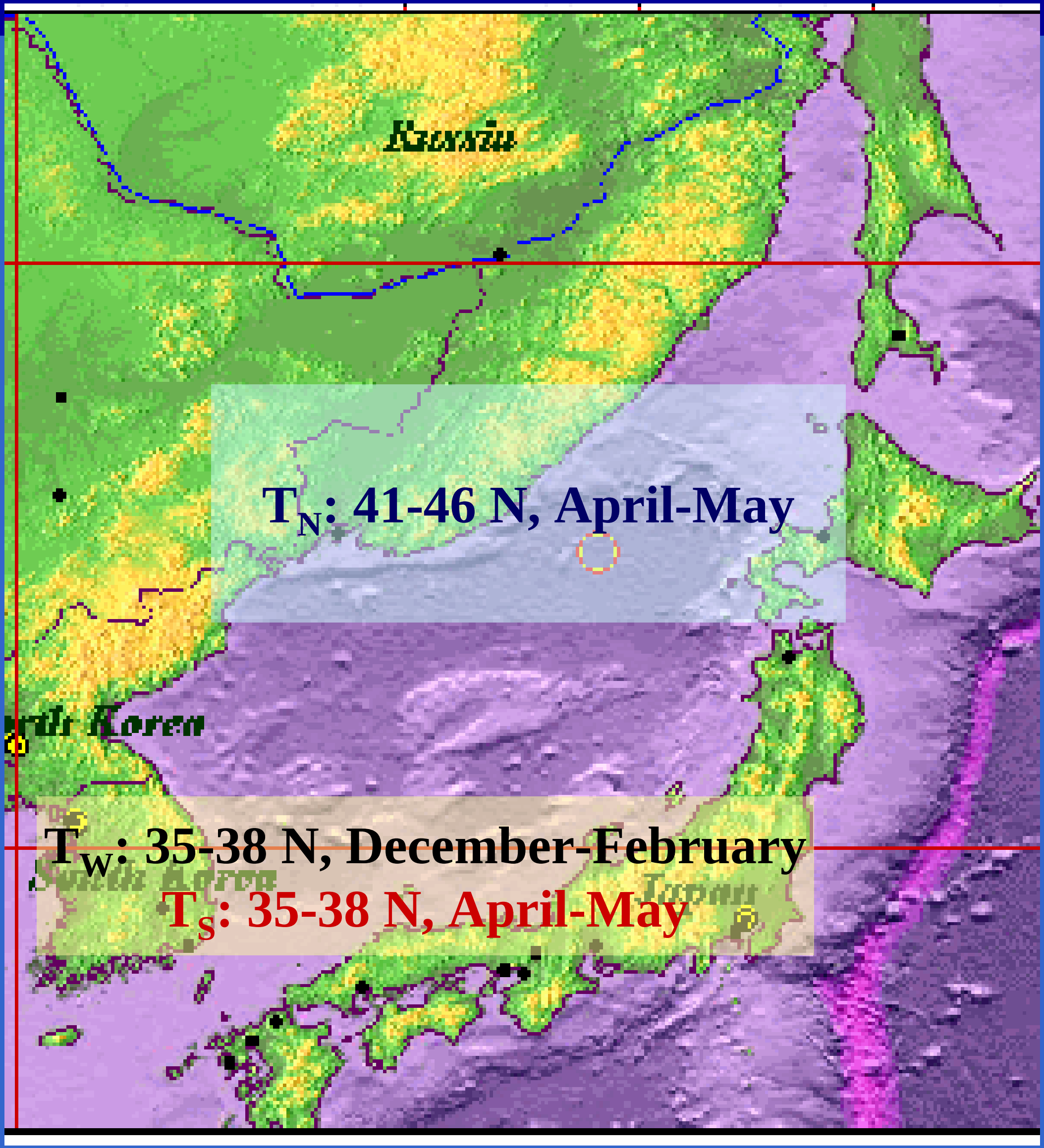
T_N is indicator of feeding conditions on feeding grounds which depends on spring SST

T_W is thermal conditions in winter, before spawning

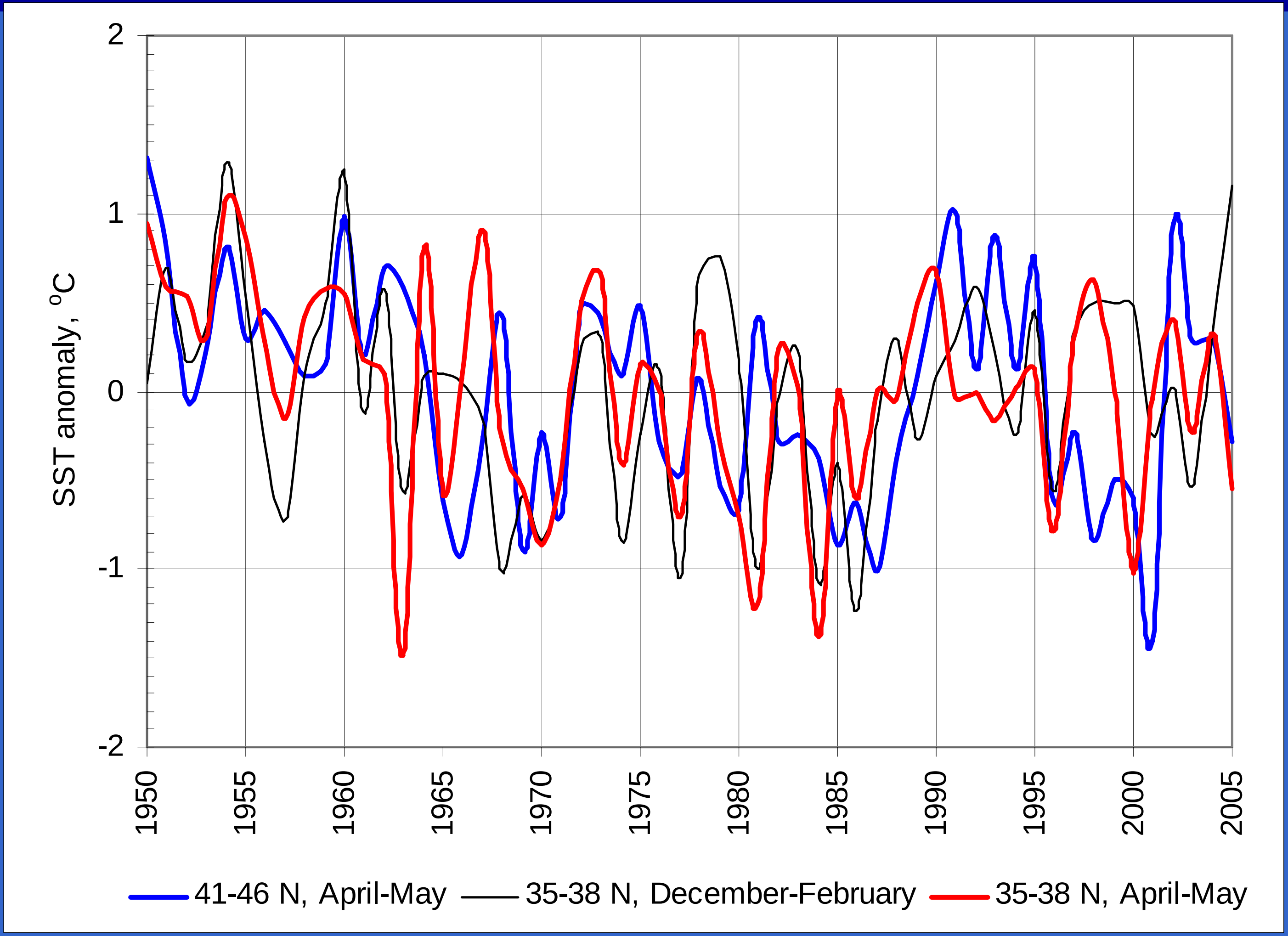
T_S is indicator of feeding conditions for larvae which depends on spring SST

Besides, **T_W** and **T_S** are used for quantitative estimation of the Cushing factor:

$M = (T_w - aT_s - b)/(a^2+1)^{1/2}$



SST year-to-year fluctuations



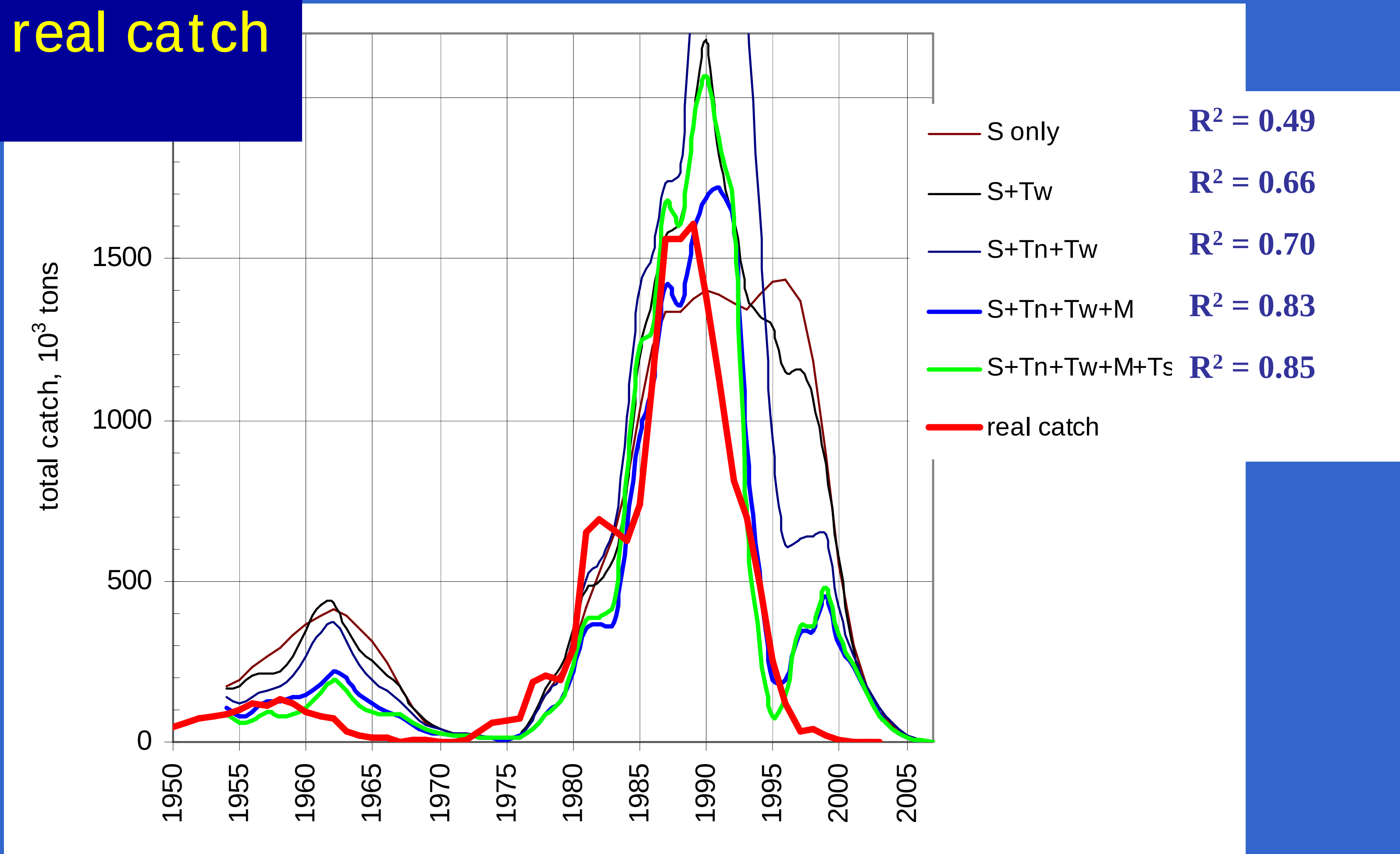
General tendencies are similar in both areas and seasons, but in some years the anomalies are very different between them

All factors are statistically independent, with exclusion the significant positive correlation between T_W and T_S

Correlation matrix

	stock	T_W	T_S	T_N	M
stock		-0.10	-0.05	-0.17	-0.01
T_W	-0.10		0.55	0.16	-0.15
T_S	-0.05	0.55		0.12	-0.08
T_N	-0.17	0.16	0.12		-0.10
M	-0.01	-0.15	-0.08	-0.10	

Fitting the model to the real catch data



The best simulation was done by the model which included all 5 environmental predictors

$$S_j = \Sigma_{i=3,4,5,6} \left[K * S_{j-i} * (f + k_N T_{N(j-i-1)} + k_W T_{W(j-i)} + k_S T_{S(j-i)} + k_M M_{(j-i)} + k_D S_{j-i}) * (1-m)^i\right]$$

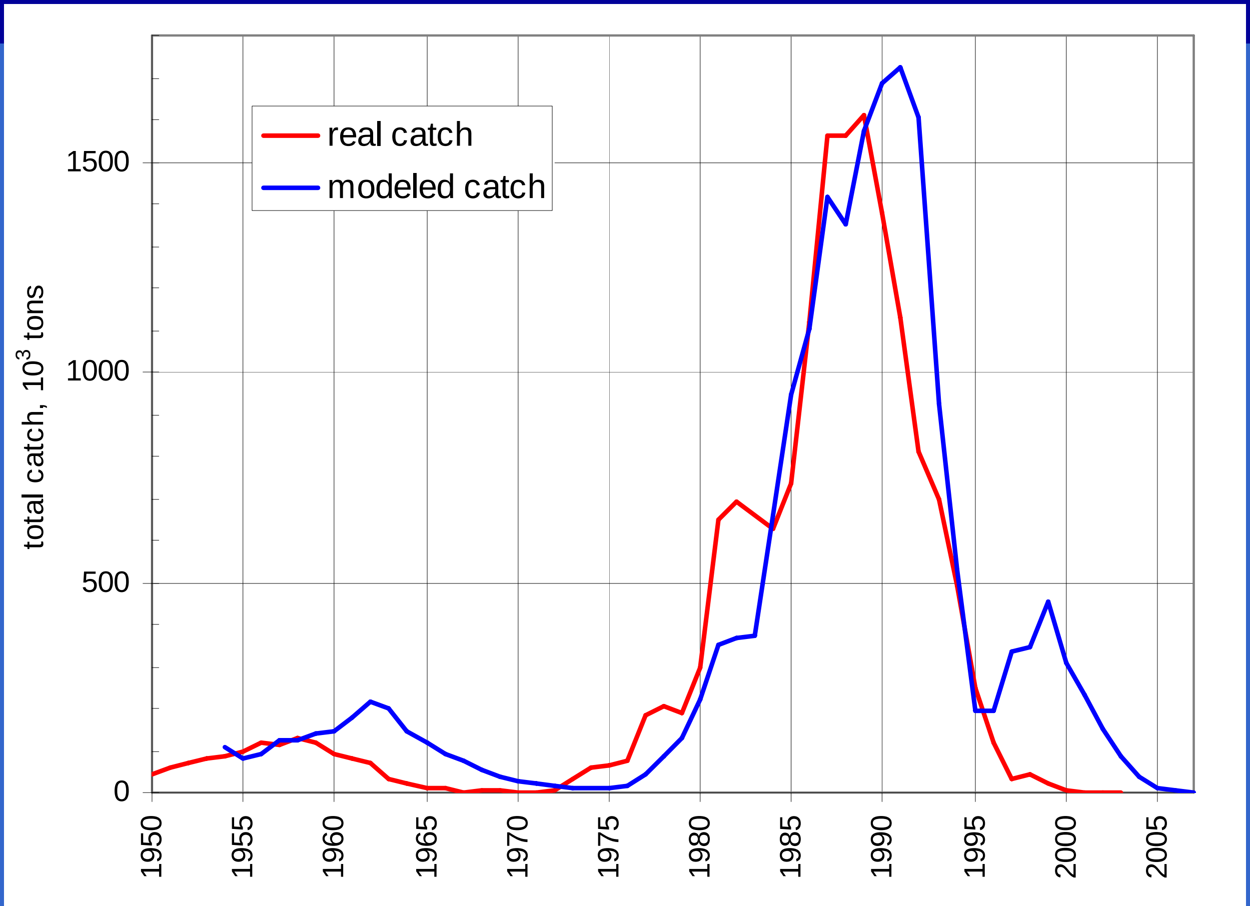
but two of them (T_W and T_S) were statistically dependent

For the best fitting, the values of coefficients are:

$K=0.4$; $f = 2.41$; $k_N= -0.67$; $k_W= -0.52$; $k_S= -0.43$; $k_M= -1.37$; $k_D= -0.0004$; $m = 0.23$

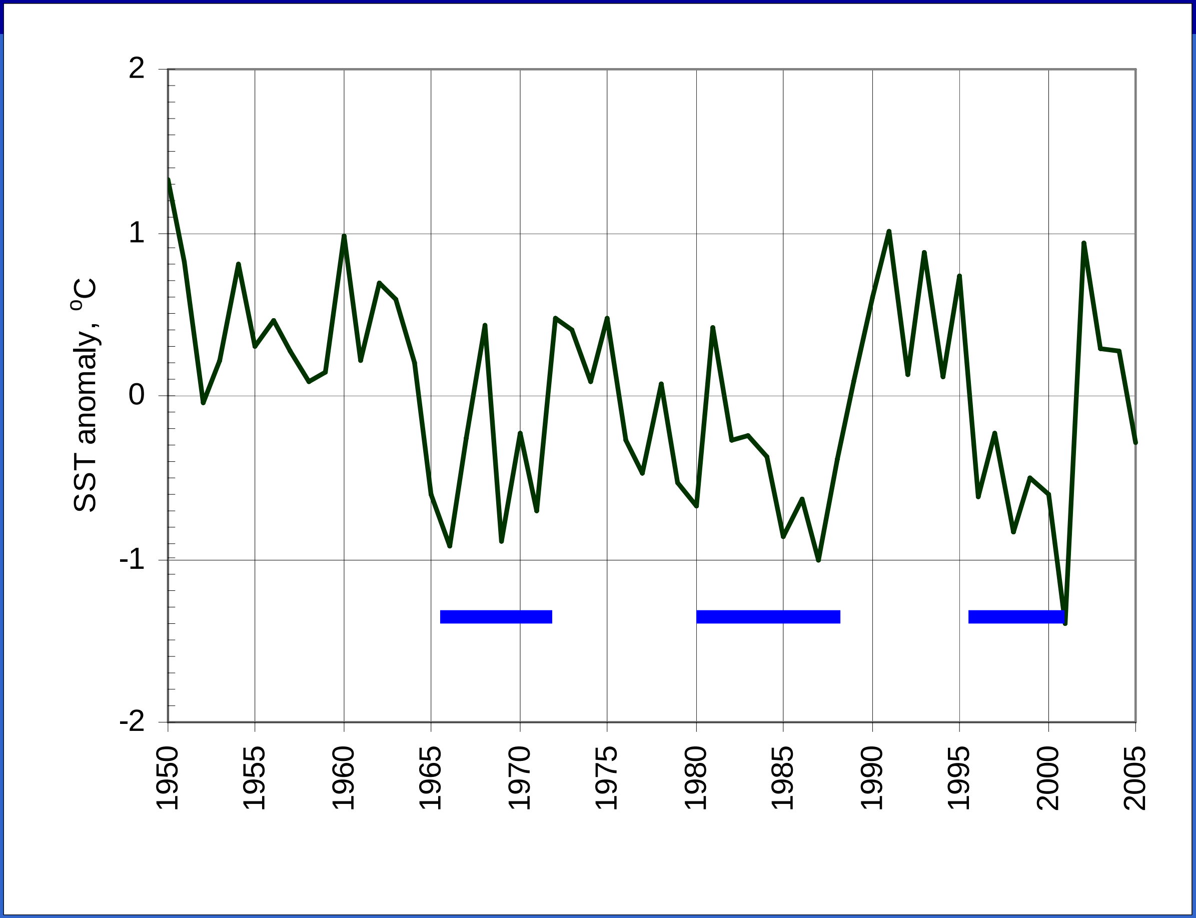
After the T_S exclusion, the final model has 4 independent predictors: S, M, T_N, and T_W

$$S_j = \Sigma_{i=3,4,5,6} [K*S_{j-i} (2.41 - 0.67\, T_{N(j-i-1)} - 0.52\, T_{W(j-i)} - 1.37\, M_{(j-i)} - 0.0004\, S_{j-i}) * 0.77^i]$$



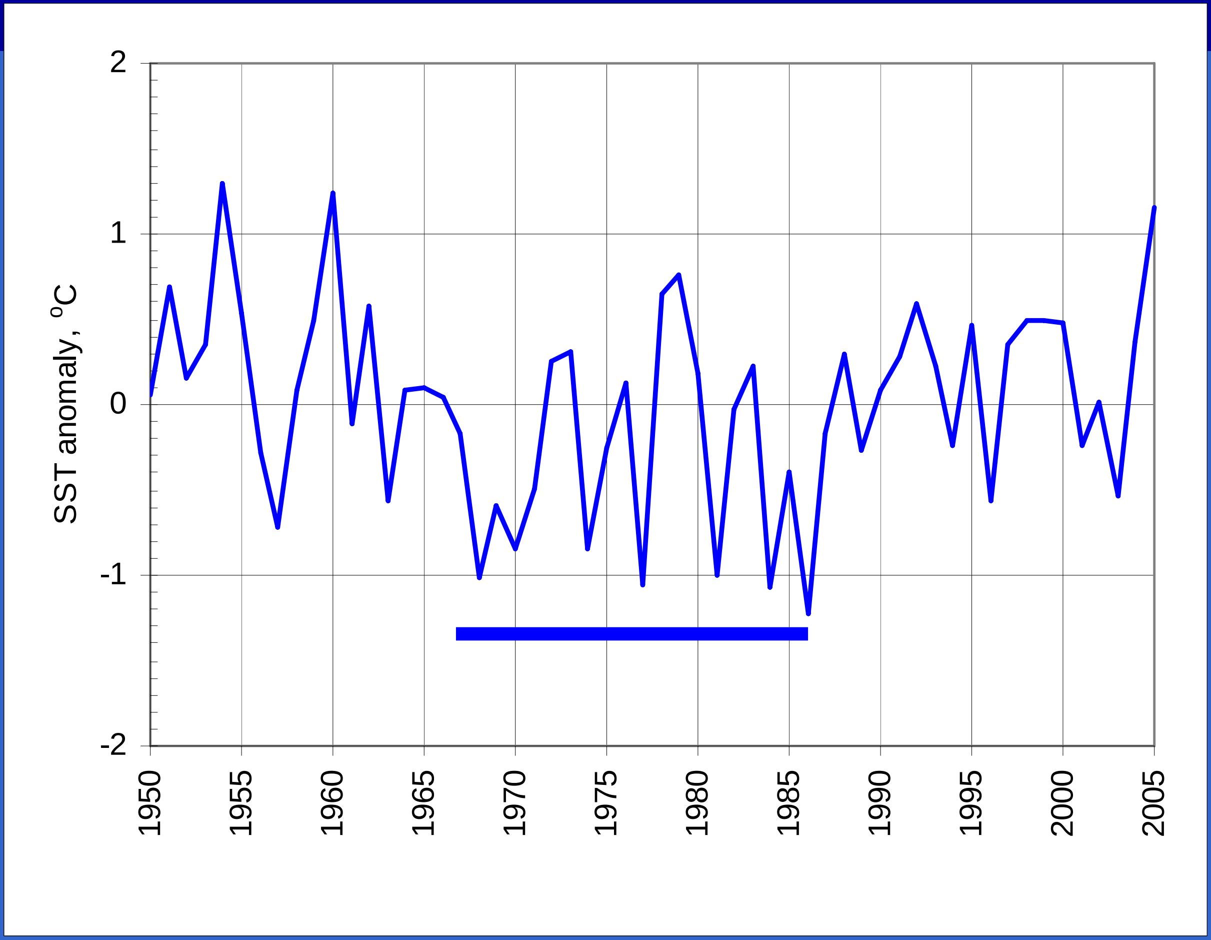
Following the model, the years with low SST on feeding grounds in spring and low and stable SST on spawning grounds are favorable for sardine reproduction

Periods of low spring SST (high plankton abundance) on feeding grounds were: late 1960s, early 1980s, late 1990s



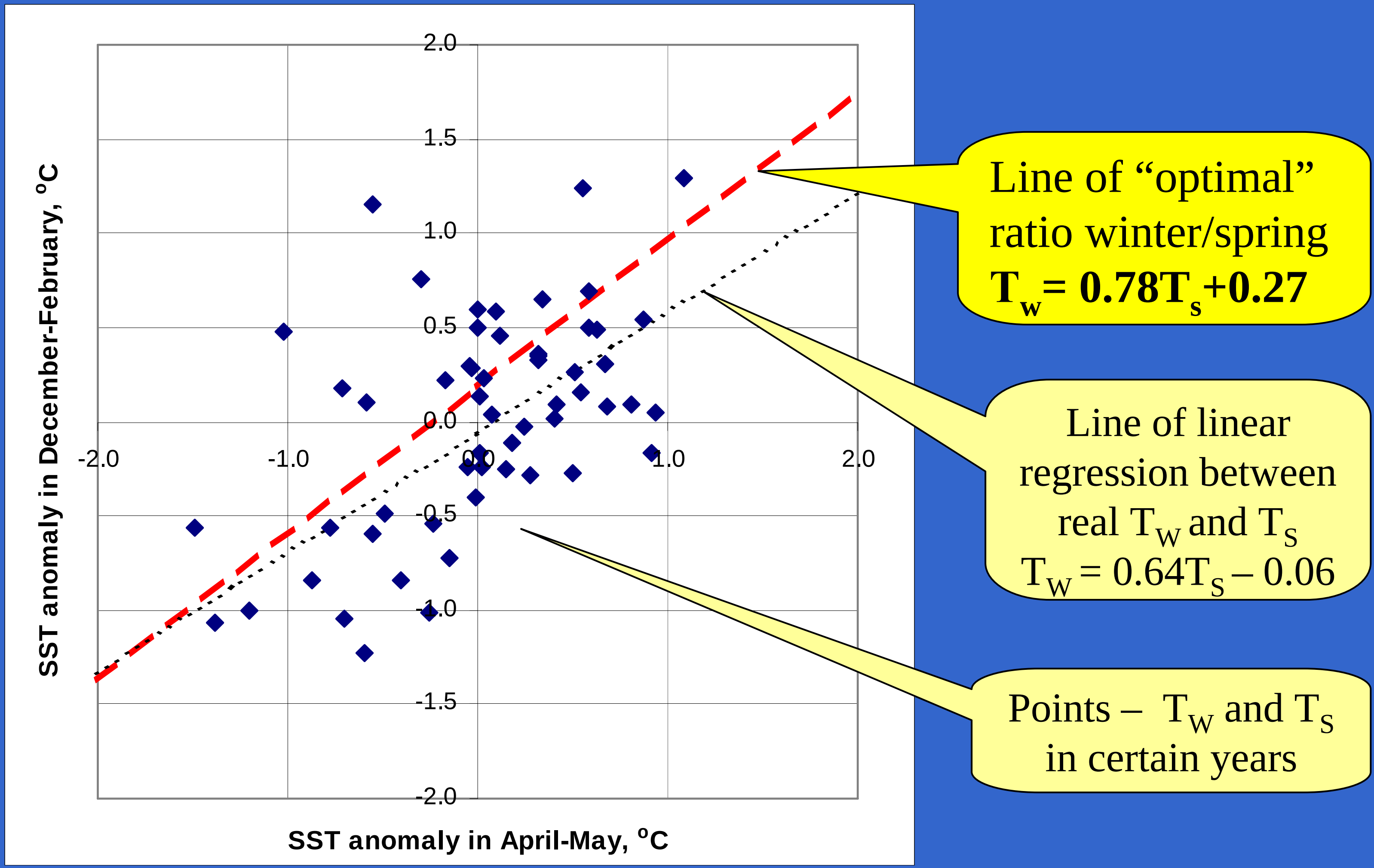
Sardine stock began to increase in the first period, reached the maximal value after the second, but the last cooling didn't stop the disaster

Period of low winter SST on spawning grounds continued from late 1960s till middle 1980s



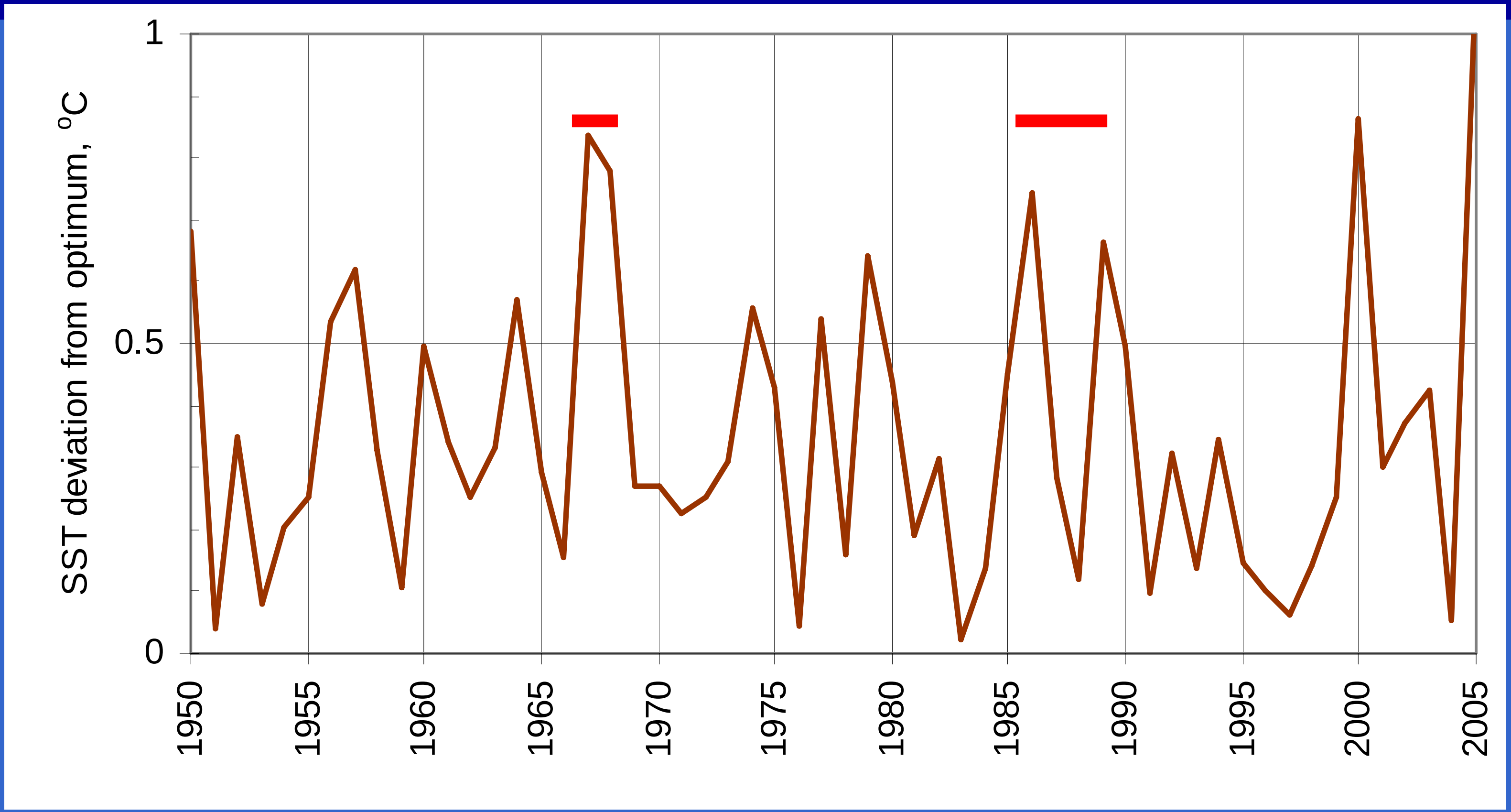
During this period, the stock of sardine increased considerably

“Optimal” for sardine ratio between winter and spring SST



The coefficient a > 0, that means the stable anomalies are “preferable” for sardine reproduction

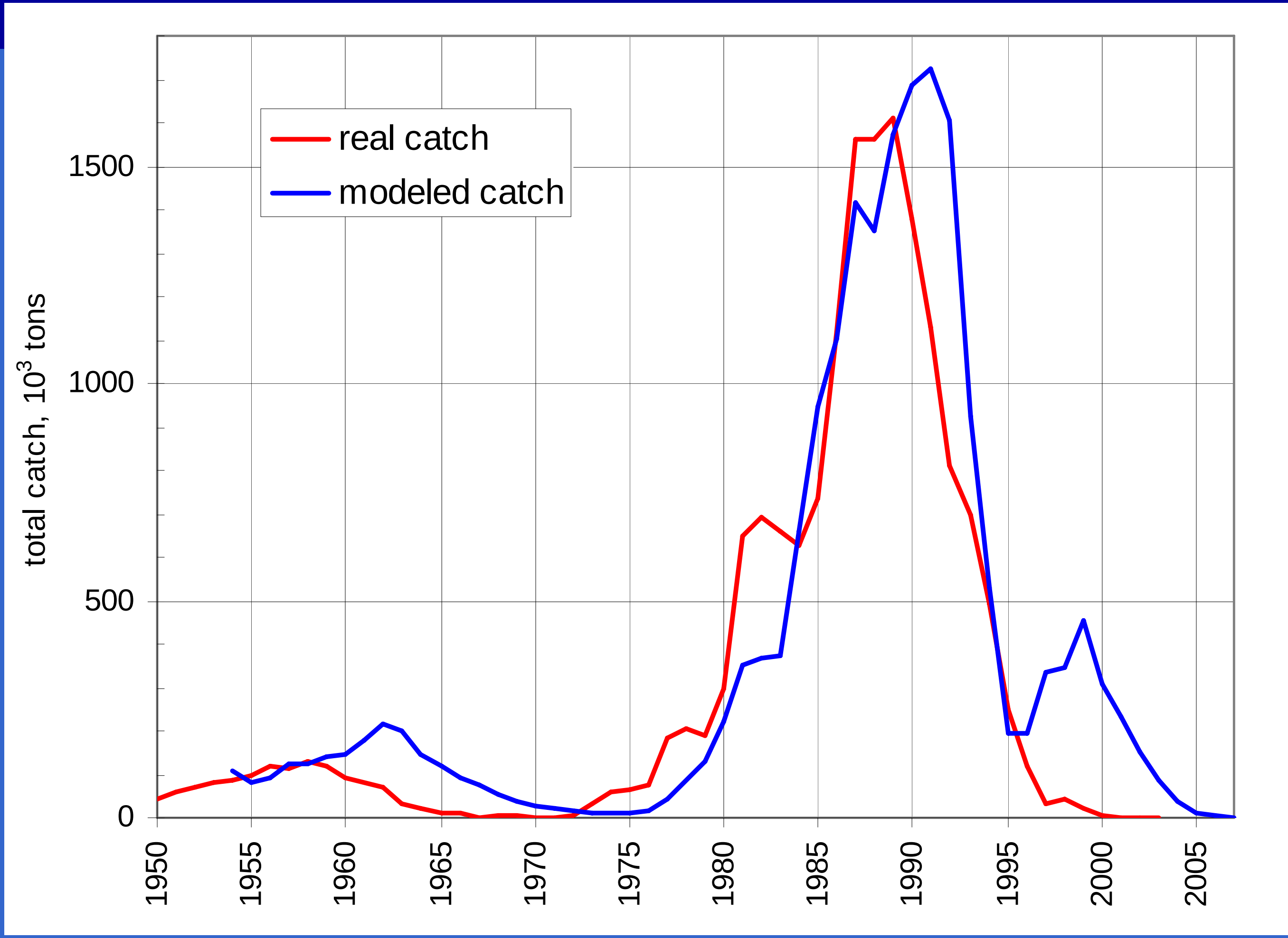
Ratio between winter and spring SST on spawning grounds was usually favorable for sardine reproduction, but in late 1960s and late 1980s it was unfavorable



The first period possibly delayed the beginning of sardine bloom, and the second was one of the reasons of its finishing

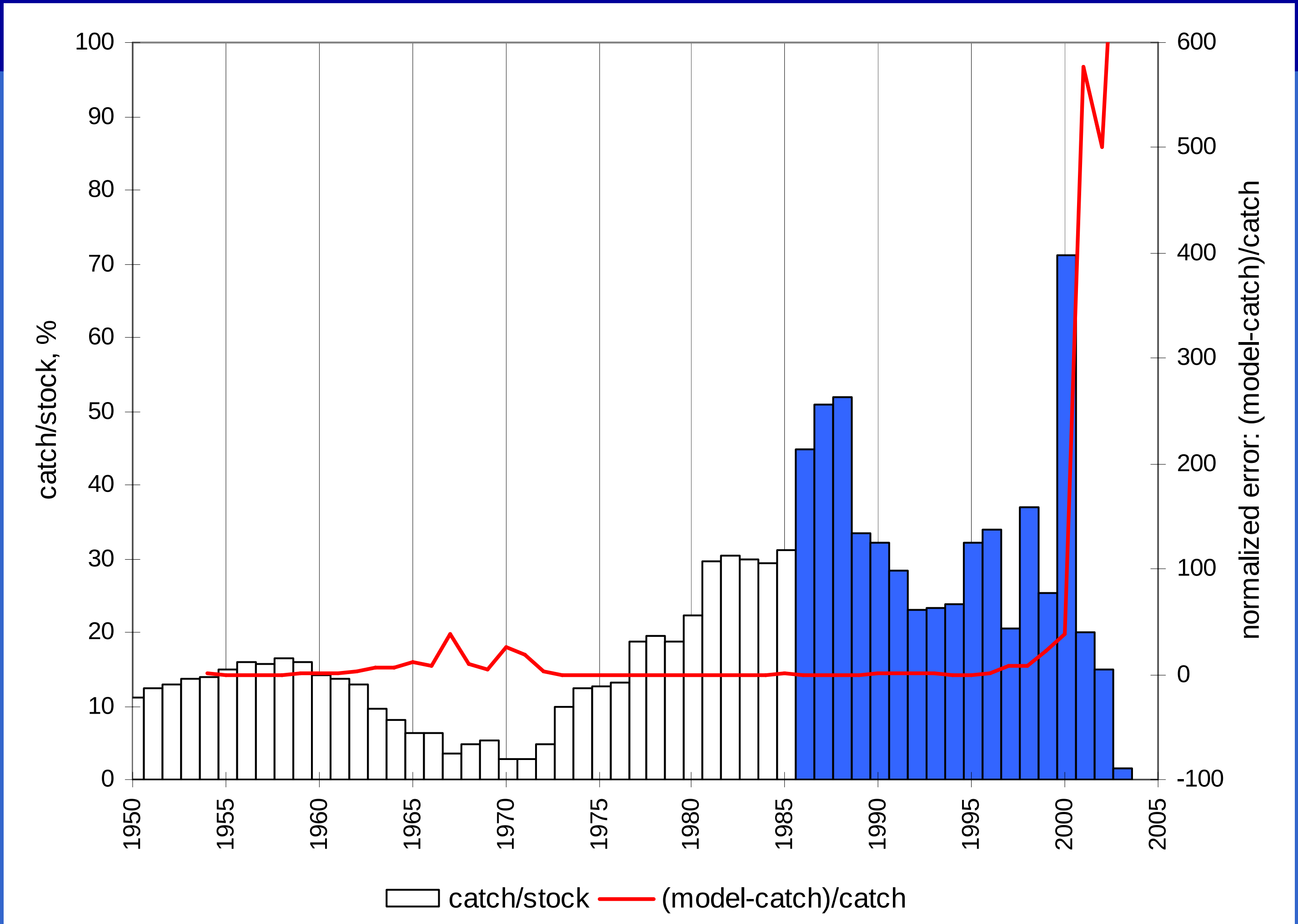
However, in late 1990s all environmental factors were favorable for sardine, and spawning stock was still considerable. So, the model predicts restoration of population.

Why was the model wrong in late 1990s?



We suppose that it was reasoned by influence of fishery, not included in the model

In our opinion, the restoration was interfered by overfishing



Annual catch of sardine was usually about 1/5 of its stock, or less in the years of low stock. In opposite, it began to increase after 1995 and reached 70% in 2000.

Conclusion

1. Multiple regression density-dependent reproductive model simulates the sardine catch fluctuations satisfactory (R^2 = 0.83) when consider the main environmental factors, both for feeding grounds and spawning grounds.

2. The most important for sardine reproduction environmental factors are:
   - thermal (=feeding) conditions on feeding grounds in the year before spawning;
   - thermal conditions on spawning grounds in winter;
   - match of the time of larvae hatching with the time of plankton blooming.

3. Spring SST on spawning grounds are not important itself for survival of the sardine larvae, although its correspondence with winter SST is important for matching the times of hatching and blooming.

4. The sardine stock fluctuations are caused by natural factors mainly, but overfishing is able to distort the natural process significantly. The overfishing prevented restoration of the sardine stock in late 1990s when environmental factors were favorable for successful reproduction of this species.

5. Recent environmental conditions are unfavorable for the sardine reproduction.

Good bye!