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Coastal sea level and the large-scale climate state A downscaling exercise for the Japanese Islands

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ABSTRACT

A major problem which is envisaged in the course of man-made climate change is sea-level rise. The global aspect of the thermal expansion of the sea water likely is reasonably well simulated by present day climate models; the variation of sea level, due to variations of the regional atmospheric forcing and of the large-scale oceanic circulation, is not adequately simulated by a global climate model because of insufficient spatial resolution. A method to infer the coastal aspects of sea level change is to use a statistical "downscaling" strategy: a linear statistical model is built upon a multi-year data set of local sea level data and of large-scale oceanic and/or atmospheric data such as sea-surface temperature or sea-level air-pressure. We apply this idea to sea level along the Japanese coast. The sea level is related to regional and North Pacific sea-surface temperature and sea-level air pressure. Two relevant processes are identified. One process is the local wind set-up of water due to regional low-frequency wind anomalies; the other is a planetary scale atmosphere-ocean interaction which takes place in the eastern North Pacific.

1. Introduction

This paper is organized in the following way. In Subsection 1.1 we discuss the problem of estimating the details of coastal sea level in the framework of climate change and in Subsection 1.2 we outline a technique, named "downscaling", to adquately do the estimation. The observational data, which we have used are described in Section 2. Results obtained with "regional" ("large-scale") forcing fields are presented in Section 3 (Section 4). In this context "regional" refers to a length scale of a couple of thousand kilometers whereas "large-scale" represents the North Pacific basin. The resulting downscaling model is applied to reconstruct historical variations and to interpet the output of a climate change experiment in Section 5. The concluding Section 6 discusses the relative merits of our technique and speculates about the physical mechanisms involved.

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1.1. Sea level and climate change

In the often controversy debate on the specifics of expected climate change the sea level stands out as one of the few climate parameters, for which most experts agree on the sign of the expected change, namely a rise. The scientific community widely accepts the view that the increased concentration of greenhouse gases in the atmosphere will increase the near-surface temperature and, through the process of thermal expansion of the sea water, the sea level (Warrick and Oerlemans, 1990). Using the output of elaborated ocean general circulation models, either coupled to a atmosphere general circulation model (Cubasch et al., 1992, 1994) or driven with the output from climate models (Mikolajewicz et al., 1990), spatial distribution of global sea level rise were derived. These distributions exhibited well organised spatial differences on the scale of thousands of kilometers.

Climate models are the only tools to derive the details, in terms of spatial resolution and magnitude, of the expected climate change. Such models are, however, limited in their spatial resolution. Even if the grid, which is used for the discretization of the differential equations, is of the order of several hundred kilometers, does a climate model hardly offer useful information on that nominal minium spatial scale. The reason for this failure is in the inadequate representation of sub-grid-scale information, as the details of orography or the coastal configuration, and in the disruption of the nonlinear energy cascade at the lowest end of the spectral resolution in the atmospheric models (von Storch, 1993).

1.2. Downscaling as a means to derive local information

We therefore suggest the use of a statistical model to infer the local details of sea level change from the (potentially) reliably simulated large-scale features in the ocean and in the atmosphere. For this approach von Storch et al. (1993) coined the expression "downscaling". Observed records of local sea level are linked through a statistical model to observed variables which represent the large-scale state. The free parameters in the statistical models are tuned with the observed data. Then, the large-scale output of a climate model is fed into this statistical model and estimates of the local sea level change are obtained.

For the design of such a downscaling procedure we have to examine the various processes which contribute to the local sea level. Three groups of processes are active, the geological processes, the regional-scale dynamical processes and the large-scale dynamical processes (see, e.g., Patullo et al., 1955; Lisitzin and Patullo, 1961; Gill and Niiler, 1961; Wyrtki, 1990; NRC, 1990; Emery and Aubrey, 1991).

• The geological processes are the redistribution of mass in the earth and the change of geometry. These processes are very slow and may be considered linear, or even absent, on time scales of decades of years. If we subtract the linear trends from the local sea level, these processes will efficiently been filtered out.

• Regional scale processes comprise the inverse barometric effect of more or less air pressing on the surface of the ocean, the steric effect of the water body being more or less dense (as a consequence of changing temperature or changing input of fresh water) and the effects of the local oceanic and atmospheric circulations (including wind set-up and wave set-up). Near the mouth of a river the streamflow of the river will influence the local tide gauge.

The accuracy with which these processes are simulated in present-day climate models (with typical horizontal resolutions of 5°) is different. The invers barotropic effect depends only on the large-scale atmospheric pressure and is therefore likely well simulated. The steric effect depends on such regional effects like the cloud cover or the availability of mixing energy, which is less well described by atmospheric models. The effects of local ocean currents, local coast lines and river streamflows are not included in such models.

• The change of the volume of the ocean is an important dynamical process which affects coastal sea level. Processes which change the volume of the ocean are the accumulation, melting and calving of glaciers and the thermal expansion (Warrick and Oerlemans, 1990). Also the large-scale circulation is important dynamical factors which contributes to small scale sea level variations.

Climate models do not describe the interaction with the glaciers, but they are powerful in the description of the gradual warming, as a consequence of global warming, and of the large-scale circulation. The effect of the modified large-scale circulation on coastal seas is misrepresented because of an insufficient description of the coastal details.

We suggest the following statistical model to specify local sea level change. First, the anomalous sea level $s_i(t)$ at station i at time t is approximated by

$$s_i(t) \approx \bar{z}_w(t) + \sum_k z_k(t)(\boldsymbol{p}_k^{\mathrm{sl}})_i \quad (1)$$

with time coefficients $z_k(t)$ and fixed vectors $\boldsymbol{p}_k^{\mathrm{sl}}$. The spatially constant term $\bar{z}_w(t)$ represents the changes of the volume of the ocean. The second term represents the spatially variable contribution of the large-scale circulation and the regional dynamical processes. For that purpose, we specificy the coefficient z_k as $z_k(t) = f_k(\text{forcing}(t))$. The "forcing" is a vector of variables which statisfies two conditions: First, sufficiently long homogenous time series are available to fit the model (1) to observed data. Second, the "forcing" must be well simulated by climate models. The latter condition limits the set of candidates to large- or regional-scale fields (with a scale of a couple of thousand kilometers or more), so that the number(s) $f_k(\text{forcing}(t))$ may be understood as indices of the large- or regional-scale state of the ocean or of the atmosphere. Then, the former conditions limits the candidates practically to sea-level air-pressure and to sea-surface temperature distributions.

We specify the functional form of the function f in a linear manner. First the forcing fields are represented by one, or a few, patterns

$$\text{forcing}(t, x) = \sum_k \alpha_k(t)(\boldsymbol{q}_k)_x \tag{2}$$

with some time coefficients α_j and then

$$f_k(\text{forcing}(t, x)) = \gamma_k \alpha_k(t), \tag{3}$$

with some constants γ_k. The patterns $\boldsymbol{p}_k^{\text{sl}}$ and $\boldsymbol{q}_k$ are combined into pairs with the same index k. In our case, these pairs of patterns are obtained through a "Canonical Correlation Analysis" (Hotelling, 1936; Barnett and Preisendorfer, 1987; Zorita et al., 1992). In a "CCA" two simultaneously observed vector time series are decomposed into a series of "Canonical Correlation Patterns" (like in (2)). These CC patterns are ordered in pairs in such a way that the coefficients of a pair of patterns is maximum correlated, whereas any two coefficients of patterns from different pairs have a zero correlation. The coefficients of the pairs with largest correlations form our numbers z_k and α_k in (1) and (2). The CC patterns are the vectors $\boldsymbol{p}_k^{\text{sl}}$ and $\boldsymbol{q}_k$ in (1) and (2). The constants γ_k are the (multiple) regression coefficients of the $z_k(t)$ on the $\alpha_k(t)$.

2. Data

In this study, we examine monthly mean values of sea level along the coast of the Japanese Islands, of sea-surface temperature and of sea-level air-pressure data in the North Pacific:

• The local sea-level data at 15 stations along the coast of Japan for the period January 1958 through December 1987 have been taken from the archives of the Permanent Service for Mean Sea Level. The positions of the 15 tide gauges is given in Fig. 1. As mentioned in the Introduction do the measurements at the tide gauges represent the relative height of the instrument to the sea level. If the height of the instrument, in coordinates relative to the geoid, changes, then does the sea level also. During an earthquake the height of the instrument may change abruptly, and it did so in July 1964 at the station Nezugaseki (number 13 in Fig. 2). The time series have visually been inspected and at one station, namely Nezugaseki, corrected.

• Fields of the North Pacific (20°N–60°N, 115°E–80°W) sea-level pressure were available on a 5°×5° longitude×latitude grid. Such fields,

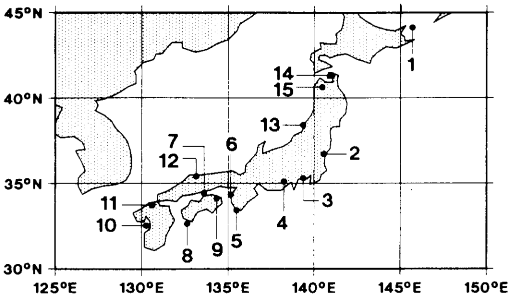

Fig. 1. Distribution of tide gauges from which data are used in the present analysis.

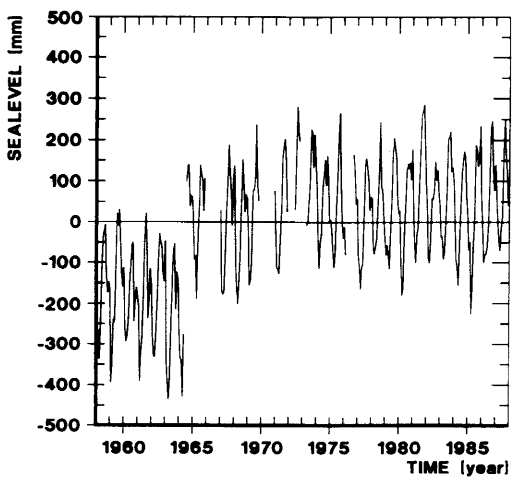

Fig. 2. Time series of monthly mean sea level at Nezugaseki (Station 13). The abrupt change in July 1964 is due to an earthquake.

which have been prepared by NCAR, are available for the time interval January 1958 until December 1987.

• Fields of sea-surface temperature were available from COADS (Woodruff et al., 1987; Cayan, 1990) for the period January 1958 until December 1986. For the seas surrounding the Japanese Islands we used a resolution of $2^\circ \times 2^\circ$ and for the full North Pacific we used the data after an interpolation on a $10^\circ \times 4^\circ$ longitude × latitude grid.

The data have been processed in the following steps.

• Japanese Islands are tectonically active. The northern east coast sinks with a rate of up to -10 to -20 mm/year whereas the west coast rises by a few mm/year (Aubrey and Emery, 1986). These rates are estimated mainly from the sea level data itself so that we can not correct the sea level data with these estimates to "clean" the data from tectonic influences. With the implicit assumption that all tectonic movement is linear on a time scales of a few decades we have subtracted the linear trend from the sea level data. Likely, other non-climatic effects such as land subsidence owing to the withdrawal of water or hydrocarbons in the neighborhood of the tide gauges (see, e.g., Emery and Aubrey, 1991) are also diminished by the subtraction of the linear trend. Since the linear trend could also incorporate a climate signal, also from the climate time series the linear trends have been substracted.

• From all data the annual cycle has been removed by first calculating a long-year mean January, February, ... field and by then subtracting from each individual monthly mean field the long term mean field.

• On the time scales of 2 years the El Niño phenomenon contributes significantly to the variability of all considered fields. Since we are mostly concerned about longer time scales, namely of the order of several years, we time-filtered the data with a 25-month running mean filter. Another reason for disregarding the ENSO phenomenon is that this process is not resolved in present-day coupled ocean-atmosphere climate models.

We examine the time-filtered vector of 15 monthly mean sea level anomalies by an EOF analysis. The first four eigenvectors represent 62 %, 16 %, 9 % and 6 % of the total variance. The pattern of the first EOF and its coefficient time series are in Fig. 3. The first EOF is positive at all stations with a maximum value of 0.37 at station 9 and a minimum of 0.05 at station 13. The time series exhibits a marked low-frequency variation with two minima in 1963 and 1984 and two maxima in 1959 and 1973–1975. Because of the shortness of the times series, nothing can be said whether the "period" of 22 years really reflects an oscillatory behaviour or represents just the time between two consecutive random passages of the zero. The time series in Fig. 3 is remiscent of low-frequency modes identified by Xu (1993). These modes are of planetary spatial scale so that the sea level variations along the Japanese coast may be

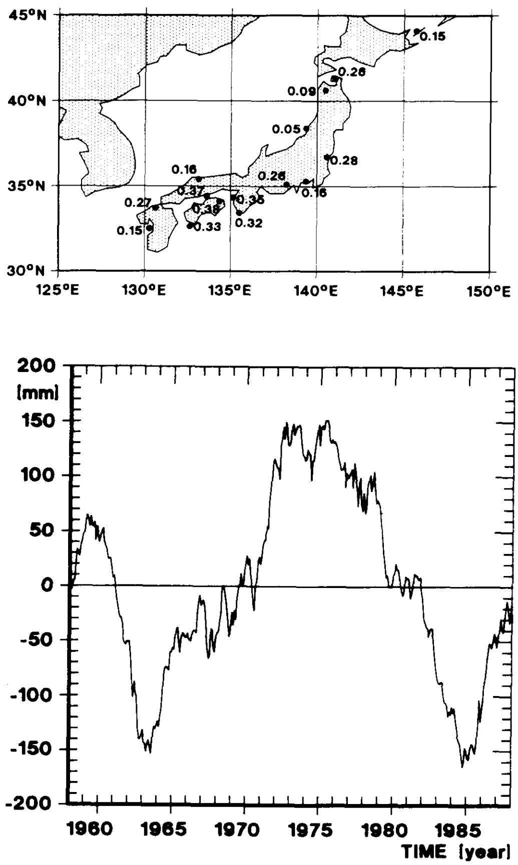

Fig. 3. First EOF of the filtered monthly mean sea level at the 15 stations (shown in Fig. 1) derived from 30 years of data (1958–1987). Top: Pattern in dimensionless units. Bottom: Coefficient time series in mm.

related to large-scale variations in the climate system.

To get an impression of the size of the anomalies we have to multiply the EOF coefficients, which vary between ± 150 mm, with the values of the EOF pattern at the stations. For station 9 we find largest low-frequency sea-level anomalies of $\pm 150 \times 0.37 \approx 55$ mm and for station 13 $\pm 150 \times 0.05 \approx 8$ mm. Recall that these anomalies are deviations from the 30-year linear trend.

3. Regional forcing of Japanese sea level variations

Subsection 3.1 describes the influence of regional circulation anomalies, as represented by the regional sea-level pressure distribution, on the Japanese sea level variations. Also the importance of the inverse barometric effect is considered. To specify regional steric effects, mainly as a result of regional temperature changes, we analyse the regional sea-surface temperature in Subsection 3.2. The tide gauge stations are not affected by large rivers so that a variable streamflow of rivers can be excluded as relevant factor.

3.1. Regional sea-level pressure anomalies

The canonical correlation analysis of sea level variations at the 15 Japanese stations and the regional sea-level pressure anomalies yields pairs of patterns which are strongly connected, with a correlation of 0.72 (see Table 1), but the canonical correlation patterns represent only little variance of the sea level in an overall sense (11%). The patterns are shown in Fig. 4 and the local rates of explained variance in Fig. 5. High pressure southeast of the islands together with anomalous low pressure in the northwest create geostrophic winds blowing parallely to most of Japanese coasts in northeastward direction. The sea level anomalies are at most gauges small and account for a negligible amount of local variance. But there are three exceptions: Typical anomalies of +25 mm at the northern part of the west coast explain 86% of the local variance, −21 mm at the northern part of the east coast represent 34% of

Table 1. *Summary of the canonical correlation analysis of Japanese coast sea level with other parameters*

CCA of sea level with:	Correlation	Explained variance of sea-level (%)	No. CCA pair
regional SLP	0.72	11.0	1
	0.34	33.0	2
regional SST	0.84	32.5	1
	0.76	30.5	2
North Pacific SLP	0.69	17.4	1
	0.44	59.7	2
North Pacific SST	0.86	22.4	1
	0.77	56.2	2

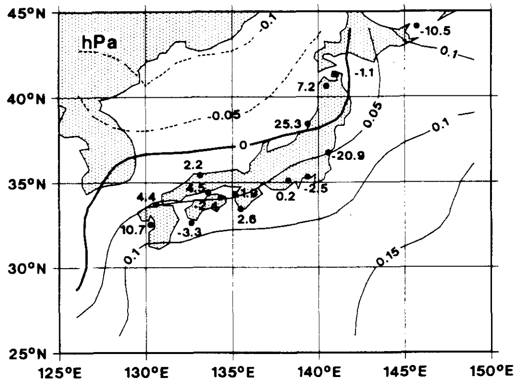

Fig. 4. 1st pair of canonical correlation patterns p_2^{sl} (dots with numbers) and q_2 (isolines) of the joint analysis of Japanese sea level and regional sea-level pressure. Units: hPa and mm.

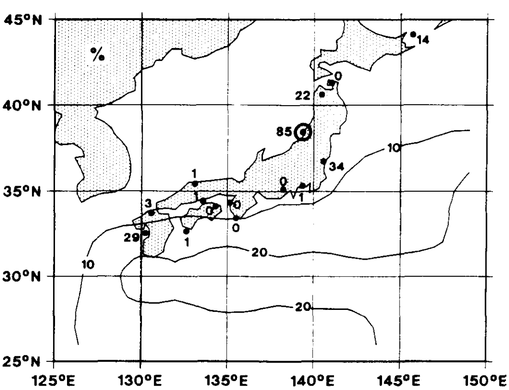

Fig. 5. Percentages of local variance accounted for by the 1st pair of canonical correlation patterns of the joint analysis of Japanese sea level (dots with numbers) and regional sea-level pressure (isolines). Units: %. Station 13, for which the local sea level time series is shown in Fig. 6, is marked by a circle.

the variance and +11 mm at the southern tip of the islands account for 29% of the variance. We suggest that the sea level in the southern part, and in particular at station 10, is controlled in part by local piling-up of water whereas the negative anomalies along the east coast and the positive anomalies along the western coast are controlled by Ekman-dynamics.

The temporal development, as given through the CCA coefficients $\alpha_1(t)$ and $z_1(t)$ in Fig. 6, exhibits low-frequency variations with typical time scales of 6 to 10 years. For comparison, the time series of time-filtered sea level anomalies at station 13, at the northwest coast, is shown in Fig. 6 also. Clearly, the CCA time series and the local sea level represent the same low-frequency behaviour. The multiplication of the CCA pattern (Fig. 4), at location 13, with the time series in Fig. 6 yields a range of $\approx \pm 50$ mm which agrees well with the range of the local variations.

To test the relative importance of the inverse barometric effect a CCA analysis was done with sea-level pressure and sea level from which the inverse barometric effect was subtracted. The results were almost unchanged to the case that the full sea level data were used (not shown).

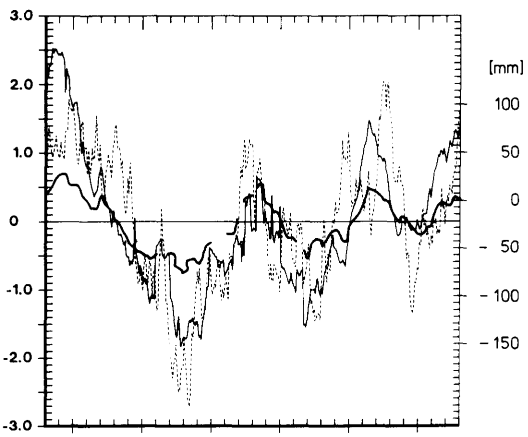

Fig. 6. Time coefficients $\alpha_1(t)$ and $z_1(t)$ of the first pair of canonical correlation patterns derived in the joint analysis of sea level (continous line) and regional sea-level pressure (dashed line). The time series are normalized to standard deviation 1. As a heavy line the time-filtered sea level anomalies at Station 13 (see marker in Fig. 5), at the northwest coast is shown for comparison.

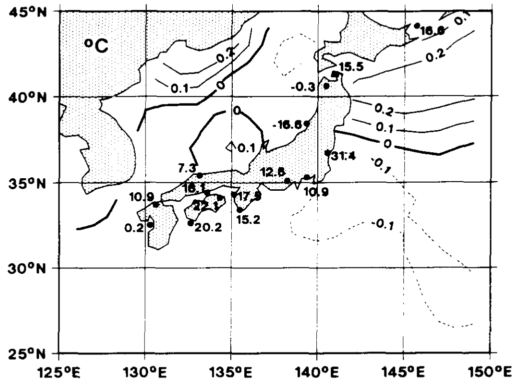

Fig. 7. 1st pair of canonical correlation patterns p_2^{sl} and q_2 of the joint analysis of Japanese sea level and regional sea-surface temperature. Units: mm and °C.

3.2. Regional sea-surface temperature anomalies

The coupling of the sea level and the sea-surface temperature is somewhat more efficient than the coupling of the sea level with the sea-level pressure (Table 1). A large correlation of the first pair is identified (0.84) with an overall description of the sea level variance of 32%. In inspection of the patterns, in Fig. 7, and of the explained local variances, in Fig. 8, reveals interesting structures. Negative SST anomalies along most of the coastline are connected with positive sea level anomalies. Negative sea level anomalies are found only for the northern part of the west coast. Clearly

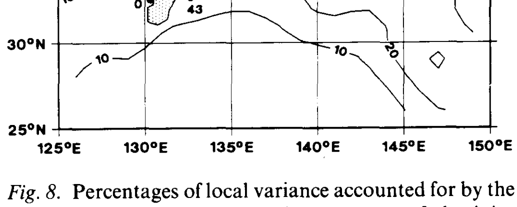

Fig. 8. Percentages of local variance accounted for by the 1st pair of canonical correlation patterns of the joint analysis of Japanese sea level and regional sea-surface temperature. Units: %. Station 2, for which the local sea level time series is shown in Fig. 9, is marked by a circle.

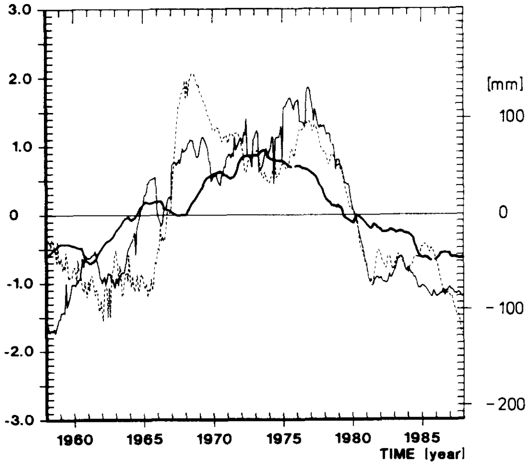

Fig. 9. Time coefficients $\alpha_1(t)$ and $z_1(t)$ of the first pair of canonical correlation patterns derived in the joint analysis of sea level (continous line) and regional sea-surface temperature (dashed line). The time series are normalized to standard deviation 1. As heavy line the time-filtered sea level anomalies at Station 2 (for the location, see Fig. 8), at the northeast coast is shown for comparison.

this pair of CCA patterns does not represent a regional steric effect but both sets of anomalies, sea-surface temperature as well as sea level, are controlled by a third process. We will see later that this process is a modification of the coastal currents. At most stations the explained variance is rather low but at the northern coast one gauge is found of which 78% of the variance is accounted for by this CCA pattern. At several other stations the rate is of the order of 40%. The maximum at 78% in sea level is connected with a rather high rate of explained SST variance, namely 40% and more. We speculate that this large effect is controlled by a change of both the Kuroshio and the Oyashio currents. If the Kurishio current extends farther north, the water movement is northeastward and the water is warm. If the strength of the Kurishio is decreased, the southwestward Oyashio current, with Ekman transport away from the coast and colder than normal water, extends further south.

4. Large-scale forcing

We have done canonical correlation analyses with the set of 15 sea level time series from the Japanese coast, on the one hand, and with North Pacific sea-level pressure or North Pacific sea-surface temperature on the other hand. The results of these analyses are summarized in Table 1.

4.1. North Pacific sea-level pressure

The canonical correlation analysis of the link between the Japanese sea level and the sea-level air pressure yields a first pair of modes which are strongly interrelated (correlation is 0.69, see Table 1) but represent only a minor portion of the sea level variance (17%). The second pair is less strongly connected, with a correlation of only 0.44, but represents a substantial amount of sea level variance (60%). The coefficient time series of this second mode, $\alpha_2(t)$ and $z_2(t)$, are shown in Fig. 10. Clearly, the large-scale sea level pressure fields exerts a marked control over the sea level on a multi-year time scale.

The two patterns, depicted in Fig. 11, indicate that a depression, with a typical core pressure of 0.6 hPa is connected with typical sea level anomalies of -25 mm in Southeast Japan and -10 mm along the coast of the Sea of Japan. Interestingly, and consistently with the findings in Subsection 3.2, does the in-situ regional atmospheric

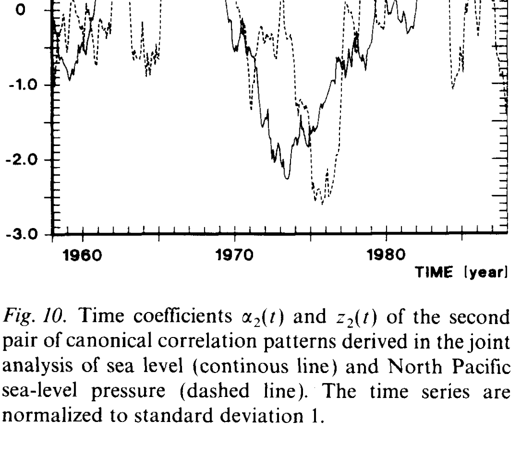

Fig. 10. Time coefficients $\alpha_2(t)$ and $z_2(t)$ of the second pair of canonical correlation patterns derived in the joint analysis of sea level (continous line) and North Pacific sea-level pressure (dashed line). The time series are normalized to standard deviation 1.

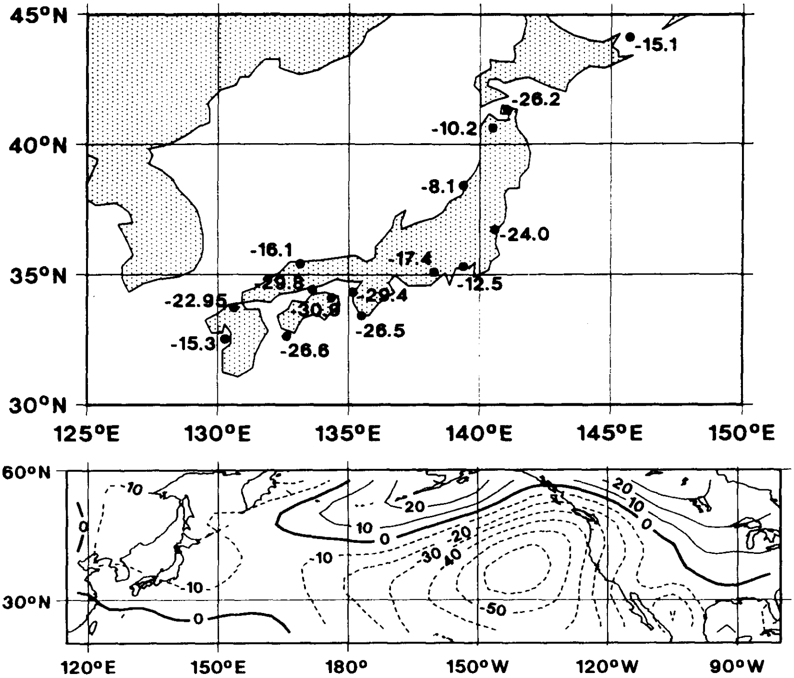

Fig. 11. 2nd pair of canonical correlation patterns p_2^{sl} and q_2 of the joint analysis of Japanese sea level and North Pacific sea-level pressure. Units: 10^{-2} hPa and mm.

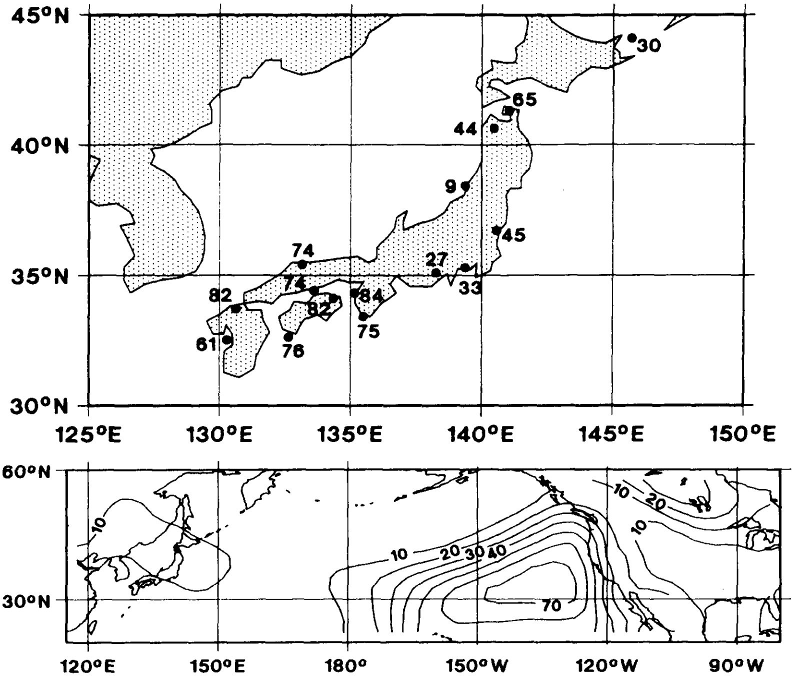

Fig. 12. Percentages of local variance accounted for by the 2nd pair of canonical correlation patterns of the joint analysis of Japanese sea level and North Pacific sea-level pressure. Units: %.

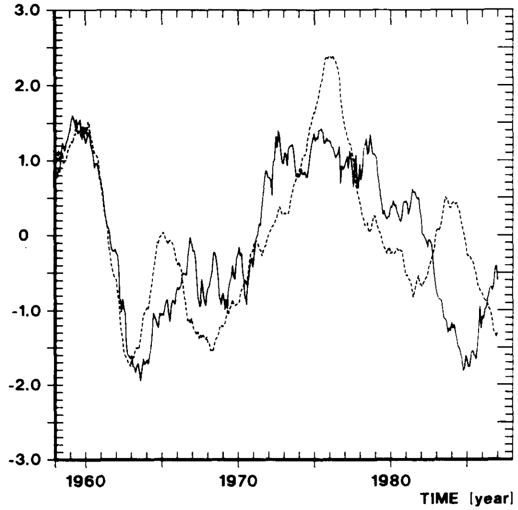

Fig. 13. Time coefficients $\alpha_2(t)$ and $z_2(t)$ of the second pair of canonical correlation patterns derived in the joint analysis of sea level (continous line) and North Pacific sea-surface temperature (dashed line). The time series are normalized to standard deviation 1.

condition contribute little to the coastal sea level variations. The atmospheric pattern explains more then 70% of the variance in the eastern North Pacific and about 10% over the Japanese Islands (Fig. 12). The success in explaining sea level variations is largest in the southern part, where percentages of more than 80% are found, and least in the northern part.

One may speculate that an anomalous atmospheric circulation over the eastern half of the North Pacific causes anomalous circulations in the ocean which, in turn, affect the sea level along the Japanese coast. We come back to this hypothesis in the concluding Subsection 6.2.

4.2. North Pacific sea-surface temperature

The canonical correlation analysis of North Pacific SST yields again a strongly linked first pair of patterns (correlation of 0.86; see Table 1) which account for only little sea level variance (22%) and a second pair with weaker connection (correlation of 0.77) but large explained sea level variance (56%). The time series of the two CCA coefficients in Fig. 13 are very similar to each other, and after a reversal of the signs, to the coefficients of the analysis of sea level pressure in Fig. 10, on the multi-year time scale.

The SST pattern, in Fig. 14, exhibits two areas of zonally arranged negative anomalies, of the order of no more than 0.25 K, which straddle a zone of almost no anomalies along 30°N. In the region surrounding the Japanese Islands, the sea-surface temperature anomalies do not affect the sea level. This pattern represents maximum SST variances in the Northern North Pacific (40%, not shown) and in the tropical West Pacific (50%).

The sea level pattern (Fig. 14) is, except for a sign reversal, similar to the pattern which was obtained in the analysis with the sea-level pressure. The explained variance range from 93% in the southern part of Japan to only 2% at the northern tip of the Islands (not shown).

5. Reconstruction of historical sea level variations and scenarios for future variations

We use the model (1), based on the first two CCA-pairs of sea level and North Pacific sea-level pressure, to reconstruct historical sea level variations from the beginning of the century. The linear trends have not beeen subtracted from the sea-level pressure in order to allow for an estimation of the climate-related trend of sea-level. Unfortunately we have no in-situ observations of station sea level data at our disposal so that we can not verify our reconstructions.

Cubasch et al. (1994) made a 150-year experiment, named "early industrial run", with a climate model. This run was forced with prescribed CO_2 concentrations. These concentrations were specified for the first 50 years of integration as the observed values from 1935 until 1985. In the remaining 100 years of the experiment the CO_2-concentrations as envisaged in the IPCC "Scenario A" were used. This set-up should tell the model to simulate the greenhouse-gas related climate change, which likely takes the form of a slow possibly accelerating trend. The naturally occuring variations on time scales of years and decades, however, in the experiment and in the observations are unrelated to each other. From the output of this experiment we have extracted

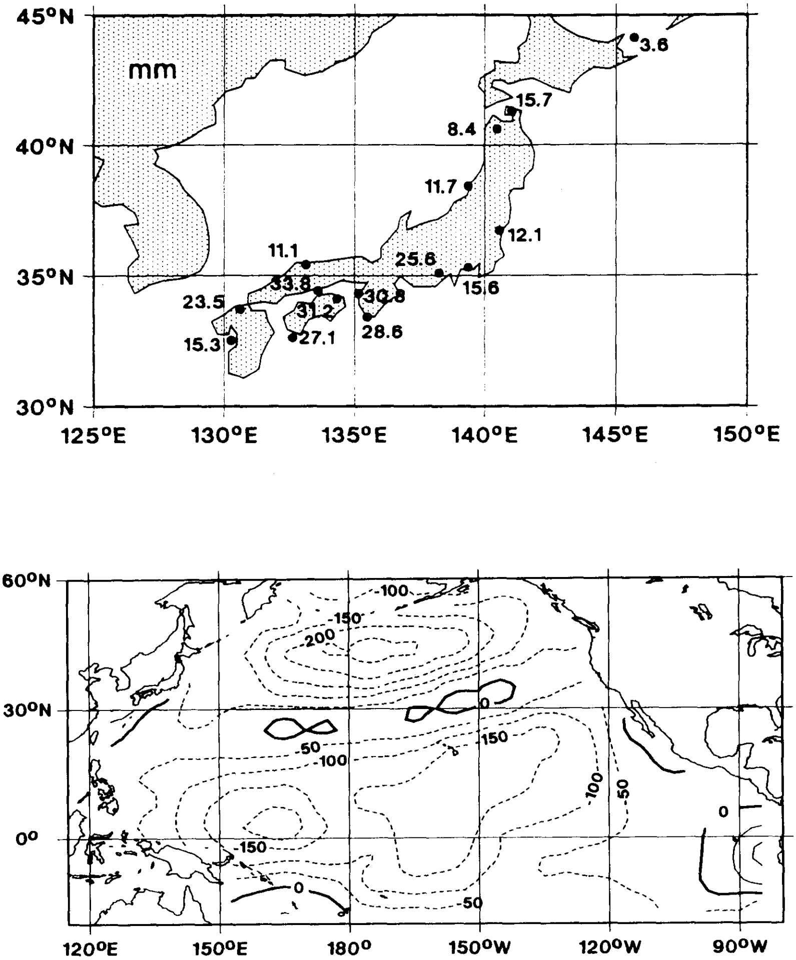

Fig. 14. 2nd pair of canonical correlation patterns p_2^{sl} and q_2 of the joint analysis of Japanese sea level and North Pacific sea-surface temperature. Units: K and mm.

the sea-level pressure fields and then fed into our downscaling machinery to analyse the possible sea level changes due to circulation changes.

The resulting curves, derived from observed SLP from 1900 to 1985 and derived from climate model output from "1935" to "2085", are shown for a subsample of six stations in Fig. 15. A striking feature is the "continuity" of the observed and simulated curves. The model seems to prolong trends, or no-trends, which have been analysed for the first nine decades of this century. At Station 2 (for the locations, see Fig. 1) sea level seems to have fallen because of changes in the large-scale environment, by about 5 cm and the model expects this fall to continue by another 5 cm in the next ninety years. At the near-by Station 4, however, the trend is reversed with an increase of about 3 cm/century. At other stations, in particular in the south, the sea-level does not exhibit systematic changes and the modification along the Sea of Japan are estimated to be of the order of ± 1 cm/century.

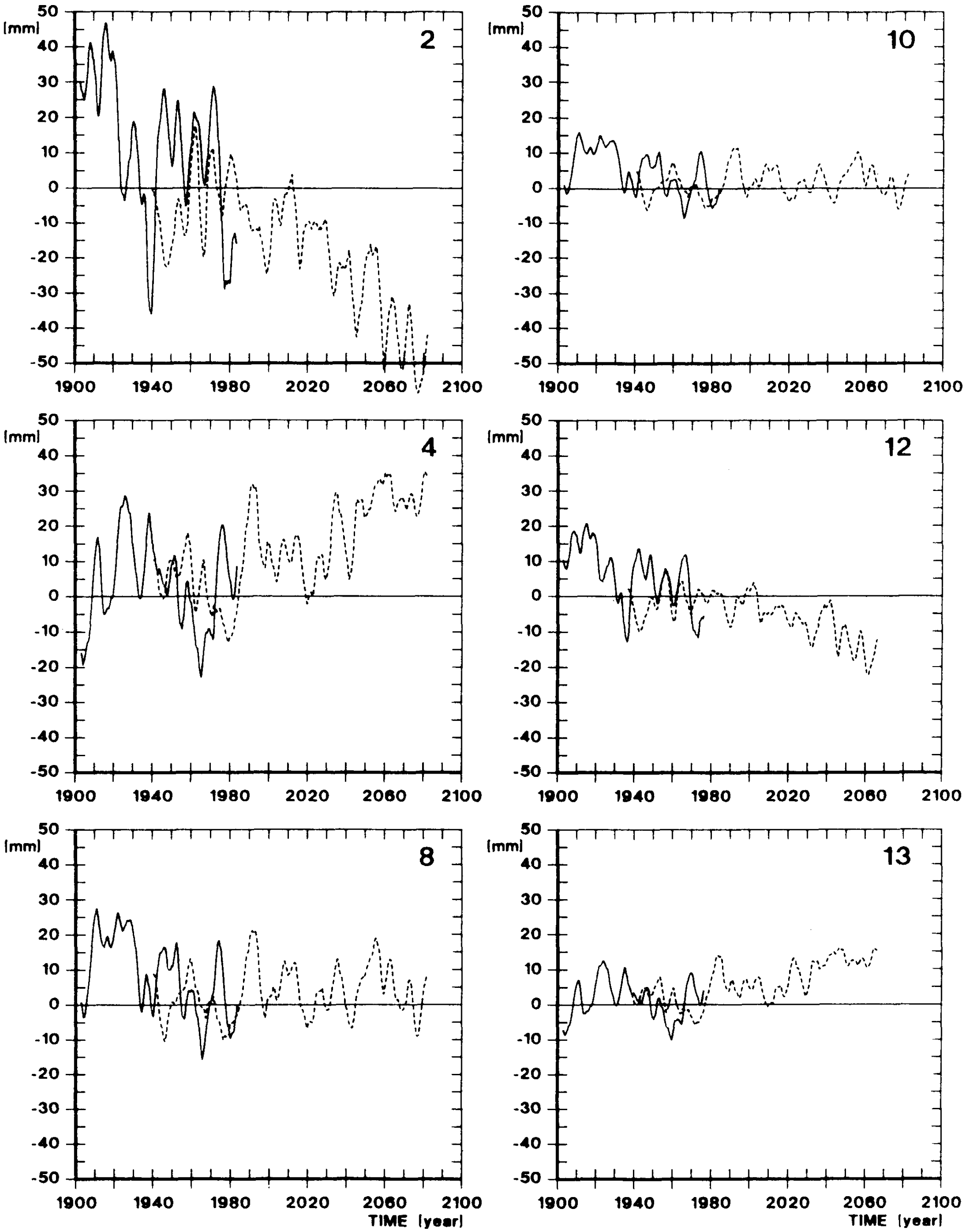

Fig. 15. Downscaled sea level changes at six Japanese tidal gauge sites as derived from observed sea-level pressure fields (continous line, from 1900 to 1988) and from simulated sea-level pressure anomalies (dashed line, from "1935" to "2085"). Only the sea-level component controlled by the anomalous large-scale circulation is taken care of by the downscaling procedure. Units: mm. For the station numbers see Fig. 1.

6. Discussions and conclusions

6.1. Method

We have used Canonical Correlation Analysis for our downscaling exercise, mainly because of lacking a-priori concepts about the significant steering mechanisms for coastal sea level. If more knowlegde is available it will be preferable to resort to other techniques which exploit such a dynamical understanding. Such other techniques might be nonlinear and could also take expected temporal lags into account.

In the present analysis we have analysed only simultaneous relationships, which reduce the skill of the procedure a bit. The rationale for doing so is the shortness of the data time series so that temporal lags of the order of 10 and more years can not be studied. Shorter time lags, however, are difficult to establish because of the temporal inaccuracy introduced by the time filtering.

6.2. Japanese coastal sea level and its forcing mechanisms

Two mechanisms seem to exert a significant impact on the (detrended) coastal Japanese sea level on time scales of several years. A regionally limited process is the wind (and, possibly, wave) set-up of the coastal seas due to local winds. A planetary scale process is related to large-scale atmospheric circulation anomalies in the eastern part of the North Pacific. This mode of variations seems to be related to the mode number 4 described by Xu (1993).

To get more insight into the dynamics of the planetary-scale process information about the temporal variation of currents and variables such as mixed-layer depth would be required. Unfortunately such information about the subsurface state of the North Pacific was not available. Therefore we used the output of two conceptually different ocean general circulation model experiments as "pseudo observations". One experiment, with Oberhuber's OPYC model (Oberhuber, 1993; Miller et al., 1992), was integrated with observed heat and momentum fluxes from the time interval 1970 until 1988. The other run was done with a primitive equation ocean model (Luksch and von Storch, 1992) coupled to a very simple atmospheric model and forced by observed winds from 1950 through 1979. From these two model runs we had the surface currents, mixed layer depth and the sea surface temperature at our disposal. With these "pseudo observations" we tried to disentangle the complex response of the oceanic dynamics to variable atmospheric conditions. Of course, model errors and experimental insufficiencies might mask the real dynamical signals. The common result, derived from both model experiments, is that the midlatitude oceanic upper layer basin-wide circulation varies in concert with atmospheric circulation anomalies in the eastern part of the North Pacific on multi-year time scales (not shown). Only the OPYC models reveals the implications for the Kuroshio, it indicates that the anomalous atmospheric circulation intensifies the Kuroshio. The hypothesis that an intensified Kuroshio lowers the sea level along the Japanese coasts can be tested with hydrographic data given by Qiu and Joyce (1992). In their time series, which cover the 1970ies and the 1980ies, the Kuroshio appears intensified during the 1980ies and weakened during the 1970ies, which is fully consistent with our description.

6.3. Historical reconstruction and scenarios for future developments

The analysis of historical variations in the atmospheric circulation over the North Pacific, as represented by the sea-level pressure distribution, reveals at some stations marked upward or downward trends of coastal sea level, with opposite signs for stations close to each other. This behaviour possibly reflects slow changes of the intensity and distributions of the gyres in the North Pacific but more work is needed to clarify this aspect.

Climate model output indicates that besides the thermal expansion of the sea water the changing circulation will be an important factor for at least some coastal stations. Maximum anomalies associated with this dynamical process are of the order of 5 cm/century.

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