Forcing Mechanisms Controlling Surface and Subsurface Temperature Anomalies along Line-P, Northeast Pacific Ocean

by

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Abstract

The influence of different mechanisms on surface and subsurface temperature anomalies is considered along Line-P, an oceanographic line extending from Vancouver Island into the Gulf of Alaska, and sampled for almost half a century. The role of a given mechanism is determined by using Canonical Correlation Analysis (CCA) between anomalies of a parameter representing the mechanism and the main Line-P temperature anomaly variations obtained from a Principal Component Analysis (PCA) performed on cast data. For each mechanism, it is determined if its direct influence can be detected, and if it can, the domain of Line-P over which it acts. Three main sections of Line-P show different behaviors. West of 130°W (offshore domain), the main mechanisms influencing Line-P temperature anomalies are Ekman transport due to zonal wind stress anomalies and wind mixing anomalies. Between 50 and 180 km offshore, upwelling anomalies, northward propagation of temperature anomalies along the coast of North America and anomalies in the strength of the Alaska Current are important in determining Line-P temperature anomalies. Closer to the coast, upwelling anomalies and alongshore wind stress anomalies along the coast of the United States are the most influential of the parameters tested.

Broad-scale anomalous situations that involve different mechanisms simultaneously are also considered. Using CCA, two broad-scale sea level pressure anomaly (SLPA) patterns associated with two Line-P temperature anomaly modes are revealed. The first SLPA pattern, consisting of an anomalously low pressure cell centered in the Gulf of Alaska, implies positive nearshore temperature anomalies along Line-P. This influence can be explained by an association with nearshore-influential mechanisms. The second SLPA pattern consists of an anomalously high pressure system centered south of Line-P, in the middle of the North Pacific Ocean (40°N, 145°W), which results in positive surface temperature anomalies in the offshore section of Line-P and negative ones nearshore. The processes involved seem to be mostly wind mixing and Alaska Current anomalies.

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Chapter 1

Introduction

1.1 Background

Temperature anomalies vary on different time scales in the Northeast Pacific (NEP), with many physical and ecological impacts inland or in the ocean. For instance, the sea surface temperature (SST) variability in the Gulf of Alaska has been related to the return of the Fraser River Sockeye Salmon (McKinnell et al., 1999; Welch et al., 1998; Xie and Hsieh, 1989), climatic and ecological variables over British Columbia, Canada, such as snow (Hsieh and Tang, 2001), streamflow (Hsieh et al., 2003), temperature and precipitation (Tang and Hsieh, 1998), prairie wheat yield (Hsieh et al., 1999) or spring flowering dates (Beaubien and Freeland, 2000).

The main interannual variability is related to El Niño-Southern Oscillation (ENSO) events, which modify oceanic conditions all along the Eastern Pacific margin. Different mechanisms are involved in this remote process. Oceanic equatorial signals propagate as coastally trapped waves from the equator up to the coast of Alaska (Enfield and Allen, 1980; Chelton and Davis, 1982; Huyer and Smith, 1985). Stronger alongshore winds are also usually associated with a strong El Niño (EN), resulting in an onshore Ekman transport changing the temperature, salinity and nutrient conditions at the coast (Simpson, 1984). These winds can also be part of atmospheric pressure systems typical of ENs, which influence oceanic conditions in the NEP on larger scales (Emery and Hamilton, 1985; Chelton and Davis, 1982; Schwing et al., 2002). The relative importance of each of these mechanisms in explaining the coastal anomalies depends on the region considered. The influence of the oceanic connection is stronger from the equator to the Gulf of California, whereas local and basin-scale winds usually have a predominant effect farther north up to the

Alaska Peninsula (Strub and James, 2002b; Enfield and Allen, 1980).

Variability of oceanic conditions in the Northeast Pacific also occurs over interdecadal time scales. During the twentieth century, radical shifts on large scales in the North Pacific have first been noticed in marine biology (Kawasaki, 1983; Lluch-Belda et al., 1989). Later, Mantua et al. (1997) introduced an index derived from North Pacific SST, the Pacific Decadal Oscillation (PDO), which can be correlated to many North Pacific climatic and biological time series (Chavez et al., 2003; Hare and Mantua, 2000).

Nevertheless, despite these two large scale NEP variability, extreme conditions also appeared in summer 2002 over more than 1500 km along the California Current, not related to a strong PDO index nor a strong ENSO event. Strong negative temperature anomalies, never observed before despite decades of records, were found in July 2002 between 30 and 150 m depth off Oregon and Vancouver Island (Freeland et al., 2003). Southward advection of anomalies in the California Current during spring and summer 2002 (Barth, 2003; Kosro, 2003), as well as zonal advection anomalies in the North Pacific Current (Strub and James, 2003), are at least part of the explanation. The current anomalies themselves seemed to be caused by large-scale atmosphere-ocean processes (Murphree et al., 2003). Nevertheless, other mechanisms may have also played a role leading to these extreme conditions.

The data used in detecting temperature anomalies off Vancouver Island were derived from observations along Line-P. Line-P is an oceanographic survey line extending from 35 km offshore Vancouver Island to Ocean Station Papa (OSP), 50°N, 145°W, in the Gulf of Alaska. Thirteen stations have been regularly sampled during almost half a century. Table 6.1 in Appendix 1 provides information about the location of the stations, which is also illustrated in Figure 1.1. The general dynamics in the region surrounding Line-P is also pictured in the plot. A broad current, called the North Pacific Current or the West Wind Drift, flows eastward and constitutes the northern limb of the clockwise sub-tropical gyre and the southern limb of the counterclockwise Alaska gyre. When it approaches the coast of Vancouver Island, it splits between a northward flow entering the Alaskan gyre, to constitute the Alaska Current (called the Alaskan Stream in the western part of the Gulf), and a southward current entering the California Current System. At the order of tens of kilometers from the shore, coastal currents can also be found, driven by fresh water inputs and by wind through upwelling (Royer, 1981a; Stabeno et al. 1995). The seasonal cycles of these currents have been considered in Strub and James (2002a).

Figure 1.1: Map showing the location of the 13 Line-P stations and a simplified sketch of the currents found in the region.

1.2 Aim of the study

The aim of the study is to determine which are the predominant forcing mechanisms influencing temperature anomalies along Line-P. This knowledge of the behavior of Line-P would be a first step to understand the temperature anomalies associated with ENSO events and the PDO index through their connections to specific forcing mechanisms. It could also help us understand the extreme conditions observed in 2002 along Line-P by a combination of different forcing anomalies.

Many mechanisms are considered in this study, including direct and remote forcing. Direct ones include:

- Ekman transport in meridional and zonal directions;
- Wind mixing;
- Ekman pumping;
- Sverdrup balance;
- Upwelling-related phenomena;

- Sensible heat transfer;
- Latent heat transfer;
- Solar and long-wave radiation related to clouds or atmospheric conditions.

For remote influence, the mechanisms studied are:

- Advection of temperature anomalies;
- Coastal wave propagation;
- Alaska Current anomalies;
- California Current anomalies.

Chapter 2

Data and Methods

2.1 Data

2.1.1 Line-P data

The original data consist of hydrographic casts performed along Line-P from May 1956 to September 2002, which includes measurements of temperature, salinity and pressure. The samples were first restricted to the farthest station P13, also called Ocean Station Papa (OSP), and were gradually performed at different locations along the line, until the 13 stations were definitively established in August 1964. The sampling along Line-P was frequent until June 1981 (approximately every 6 weeks), and was later carried out at a rate of 2 to 6 times per year. Figure 6.1 given in Appendix 1 shows the number of casts performed for each station in a given month. A more complete history of Line-P sampling is presented in Whitney and Freeland (1999).

We converted the original data into monthly data. Since the depth range and the increment between values are different from one cast to another, we interpolated temperature values to every 5 m to get a standard format. This spacing is fine enough for the phenomena we want to study. Also, we just examine data from the surface to 500 meter-depth to account for surface to mid-depth considerations. To get monthly data, we averaged all the values available in a given month for every depth increment. Figure 6.1 in Appendix 1 shows the number of casts used to get the monthly data at a given station for a given month. In most cases, a resulting datum was only derived from a few casts; so the adjective "monthly" should be carefully considered. Nevertheless, although surface conditions may vary daily, temperature is expected to vary on longer time scales as the depth increases. Hence, the accuracy of the monthly data increases with

depth.

2.1.2 Other data

2.1.2.1 Direct data

Sea level pressure (SLP), zonal wind (u-wind), meridional wind (v-wind) and wind speed data consist of monthly means obtained from the CDC (Climate Diagnostics Center) Derived NCEP (National Centers for Environmental Prediction) Reanalysis Products. Temporal coverage spans the Line-P sampling period. Spatial coverage is global with a 2.5-degree resolution both in latitude and longitude.

Sea surface temperature (SST) refers to the NOAA (National Oceanic and Atmospheric Administration) Extended Reconstructed Sea Surface Temperature. It consists of monthly means, on a global grid with a 2-degree resolution.

Cloud Forcing Net long-wave Flux (CFNLF), Clear Sky Downward Solar Flux (CSDSF), Clear Sky Downward long-wave Flux (CSDLF), sensible and latent heat net flux data used in the study come from the NCEP/NCAR (National Centers for Environmental Prediction/ National Center for Atmospheric Research) Reanalysis Surface Flux data sets. Spatial coverage consists of a T62 Gaussian grid with 192x94 points.

Finally, climatological ocean temperature values come from the NODC (National Oceanographic Data Center) (Levitus) World Ocean Atlas 1998 (<http://www.cdc.noaa.gov/cdc/data.nodc.woa98.html>). They consist of global data with a resolution of 1 degree in latitude and longitude, for different depths.

2.1.2.2 Derived data

Monthly values for the zonal and meridional wind stresses are directly obtained from multiplying the monthly means of the wind speed with the component of the wind in the given direction. The wind stress is defined as $\vec{\tau} = \rho_A c_D \|\vec{u}\| \vec{u}$, where $\vec{u}$ is the wind vector, ρ_A the air density and c_D the drag coefficient. In this study, we just use time series of wind stress anomalies for correlation purposes. Multiplying a time series by a fixed factor does not change the results of a correlation. The fact that we do not consider the density of air and the drag coefficient is equivalent to assuming them to be constant. It is an approximation since the density of air may vary and since the drag coefficient is a function of the wind speed. Another approximation consists of reconstructing wind stress monthly means from the monthly values of the wind speed and of the wind in the direction considered. The temporal average of a product is different from the product of the averaged values. Despite those approximations, we expect our data set to take into account the main monthly variations of the real wind stress.

The monthly values of the wind stress curl are directly derived from the wind stress monthly means, i.e. the derivative of the wind stress in the x and y directions were calculated from 2.5° grids.

The wind stress in a direction α is obtained by projecting the wind stress vector on the given direction:

$$\tau_\alpha = \tau_y \cos \frac{\pi\alpha}{180} - \tau_x \sin \frac{\pi\alpha}{180}$$

where α is the angle between the northward direction and the direction considered, positive counterclockwise. It means $\alpha = 0^\circ$ represents the northward direction, $\alpha = 90^\circ$ represents the westward direction.

Monthly values for the Cloud Forcing Net Solar Flux (CFNSF) are derived from daily values obtained from the NCEP/NCAR Reanalysis Surface Flux Data.

The climatological mixed layer depths are calculated from the monthly long term means NODC (Levitus) World Ocean Atlas 1994 via potential density (Monterey and Levitus, 1997).

2.1.2.3 Data source

NCEP Reanalysis, NOAA Extended Reconstructed SST and NODC (Levitus) World Ocean Atlas data are provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at <http://www.cdc.noaa.gov/>.

2.2 Methods

Canonical Correlation Analysis We want to consider the direct effect of the anomalies of a given forcing mechanism on Line-P temperature field. For that, we take advantage of the unique length of Line-P records (one of the longest in the history of oceanographic lines) to perform statistical analysis. Canonical Correlation Analysis (CCA) is a generalization of the concept of correlation between two variables to finding patterns of maximum correlation between two sets of variables (Von Storch and Zwiers, 1999, sec. 14). If $\underline{x} = [x_1, \dots, x_k]$ and $\underline{y} = [y_1, \dots, y_l]$ are the two sets of variables, CCA finds the optimal linear combinations $u = \sum_{i=1}^k a_i x_i$ and $v = \sum_{j=1}^l b_j y_j$, such that the correlation between the canonical variates u and v is maximized. The input variables can also be associated with spatial patterns, in which case the canonical variables also represent the variations of a spatial pattern. The canonical variables and associated spatial patterns are referred as CCA modes in the rest of the study. In our case, the two input sets of variables have to consist

of the main anomaly variations for Line-P temperature and for the forcing mechanism considered.

Line-P input set of variables For Line-P temperature anomalies, the input variables are the leading modes (PCs) extracted from a Principal Component Analysis (PCA) performed on the monthly Line-P temperature data set described in Section 2.1.1, after removal of the seasonal cycle at each point. A PCA indeed finds the linear, independent modes that have the largest temporal variability (sorted out with decreasing values of variance). It also filters part of the noise, which is contained in the higher modes. A regular PCA is not possible for our Line-P data set since it contains too many gaps. We use an alternative method which involves approximations (Von Storch and Zwiers, 1999, sec. 13.2.8). This one is explained in Appendix 2, where a test is also presented to show the validity of the PCA modes obtained.

The number of Line-P PCs to be used in the CCA has to be large enough to include small variability that may be associated with a given mechanism, but our data set also contains much noise, which may appear even in the leading modes. We took 9 PCs for Line-P temperature anomalies, the variance explained by the 10th PC decreasing significantly compared to the previous one (see Table 6.3 in Appendix 2). In any case, the results of this study do not change much when adding more PCs, with only increased noise in the spatial patterns.

Forcing input set of variables For the set of variables representing the main variations of the forcing anomalies, a proxy is needed to account for the mechanism considered, which usually consists of the main parameter involved in the mechanism. Once the proxy used to represent the given mechanism is determined, the input set of variables for the CCA consists of the 3 leading PCs in the case of forcing mechanisms directly acting over the surface of the ocean, or of an average of the proxy over a specific domain for other processes. For direct forcing mechanisms, the PCA is performed for the same period of time as for the Line-P PCs (May 1956 - September 2002) over a domain directly overlying Line-P. In the case of proxies derived from CDC Derived NCEP Reanalysis Products, this domain is $[47.5^{\circ}\text{N}; 52.5^{\circ}\text{N}] \times [125^{\circ}\text{W}; 145^{\circ}\text{W}]$ (3×9 points), and of $[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$ (4×13 points) in the case of NCEP/NCAR Reanalysis Surface Flux data sets. In both cases, the number of spatial points is small, which explains the use of only 3 PCs to account for the main variability over those domains. Also, adding more PCs does not change the results significantly. In the case of remote or localized forcing mechanisms, the domains used for the average of the proxies are specific to each of them and are presented in the corresponding sections. Also, in this case, the CCA input for the forcing consists of only one time series; so no spatial mode is derived for the forcing mechanism, only one for the Line-P temperature anomalies.

Filtering All the input time series used for the CCA are smoothed using a three-month running mean to decrease the level of noise for Line-P PCs and to be consistent with this smoothing for forcing variables.

Also, if we perform the CCA with all frequencies included in the input time series, long-term oscillations might explain most of the correlation found and in fact correspond to indirect broad scale variations (such as PDO). It would consequently prevent us from finding the highest correlation for higher frequencies, which are the ones we want to consider in studying the direct effect of a forcing. Therefore, in order to get the modes of maximum correlation for variations with periods ranging between a few months to a few years, we subtracted the five-year running mean from all input time series. The CCA then finds the two combinations for the two sets of variables which give the highest correlation only with respect to the higher frequencies of the input time series. Nevertheless, the real variations of the modes include all frequencies. The two combinations of variables found by the CCA (with only high frequencies considered) are then applied to the original time series (low frequencies included) to get the real temporal variations of the CCA modes, which eventually contain interdecadal oscillations. Actually, if the Line-P temperature anomaly mode was totally determined by the forcing anomaly mode, the variations of the two modes would also match for low frequencies, even if only high frequencies were considered to correlate the two. Nevertheless, since the Line-P mode always captures extra variability not directly accounted by the forcing considered, it is useful to consider how the two CCA time series match for low frequencies when nothing has been done to correlate them. This may help in seeing if the Line-P mode captures variability not accounted for by the forcing mode.

In some cases, the capture of indirect effects cannot be prevented when using statistics, since two different mechanisms can be correlated to one another. Since the anomalies of these two forcing would vary in phase, the Line-P temperature anomaly mode may not be directly related to the mechanism studied but to the other one. In fact, the more influential mechanism of the two should determine Line-P temperature anomalies. By confronting the expected influence of the forcing mechanisms to the actual results, we can determine if the 2 CCA modes can correspond to a direct effect or if another process is mostly responsible for the correlation. In each section, an introduction to the physics of the mechanism is therefore given to help interpret the results.

Lagged CCA Another issue, potentially unsolvable, is that the parameters involved in the forcing mechanism can be a function of the Line-P surface temperature itself. A coupled response can relate the proxy anomalies used to represent the forcing and the temperature anomalies along Line-P. In order to determine

if the Line-P CCA mode is mostly forced by the forcing CCA mode or if the contrary in fact occurs (the word “forcing” being in this case meaningless), we performed CCAs with different lags. We shifted the Line-P PCs with respect to the forcing input variables from -20 month to +20 month lags with an increment of 1 month, and we performed the CCA each time. The correlations and the corresponding CCA modes will be slightly different for two consecutive lags. Line-P response to the forcing is expected for the lag which gives the highest correlation. It first helps to consider if the Line-P mode indeed lags the forcing mode. It is also useful to determine the timing of the response in the case of remote forcing mechanisms, and even in the case of direct forcing when the theory uses a steady approximation (for example for Ekman transport, see Section 3.1.1). Finally, a comparison between the CCA correlations found around zero-lag (when we expect to find the response, hence the highest correlations) and the correlations at large lags (when we expect the forcing mechanism not to be acting directly, hence low correlations) helps consider the relevance of the results. Another method, more objective, is also used to determine the significance of the correlation between the two modes for the lag considered.

Significance test To test if a correlation is significant, we compute random normally distributed time series, with the same variance as the actual ones used, and perform 1000 equivalent CCAs. We can then consider the percentage of random CCAs giving lower correlations than the correlation found from the study, which gives an idea of the significance of the mode.

The problem is to find a relevant time length for the random data sets. The original time series being autocorrelated to some extent, the effective sample size is not the total length of the data. We use the first zero crossing method to determine the effective sample size. The first lag l_0 for which the autocorrelation coefficient reverses sign gives an indication of the degree of autocorrelation of the time series. A crude estimation of the effective sample size is then $N_{eff} = \frac{N}{l_0}$, where N is the number of points in the original time series. N_{eff} is different for each time series but we need only one value to generate the random tests. For each forcing mechanism studied, we used the mean effective sample size of all CCA input time series (Line-P and forcing ones) to determine the length of the random time series for the 1000 CCA runs.

Chapter 3

Results

3.1 Direct influences

3.1.1 Ekman transport anomalies

Physics The equation of the dynamics of the ocean can be simplified when considering geophysical flows. Those simplifying assumptions include the Boussinesq, the hydrostatic and the incompressibility approximations, and an aspect ratio much less than one ("*vertical scale*" / "*horizontal scale*" $\ll 1$). Looking for the steady solution with no dependencies in the horizontal directions when a steady wind stress is applied to the surface of the ocean, we find a transport 90° to the right of the applied stress in the North Hemisphere (Gill, 1982, sec. 9.2):

$$\vec{U}_E = \frac{\vec{\tau} \times \vec{k}}{\rho f}$$

where $\vec{U}_E$ is called the Ekman transport (integration of velocities from surface to bottom), $\vec{\tau}$ is the wind stress ($\vec{\tau} = \rho_A c_D \|\vec{u}\| \vec{u}$ where $\vec{u}$ is the wind vector, ρ_A the air density and c_D the drag coefficient), $\vec{k}$ the vertical unit vector (pointing upward), ρ the density of the water (assumed constant), f the Coriolis parameter ($f = 2\omega \sin \phi$ where ω is the Earth's angular velocity, and ϕ the latitude).

This transport is supposed to take place mainly at the surface in the Ekman layer, typically between 10 and 100 m deep. Wind stress anomalies will be associated with transport anomalies in this layer, and consequently in its physical properties. We expect temperature anomalies in the Ekman layer to be

proportional to the strength of the Ekman transport anomalies and the typical temperature gradient in its direction (90° to the right of the applied wind stress in the North Hemisphere):

$$T_{ET}^{(a)}(\alpha) \propto -U_{E\alpha}^{(a)} \frac{\partial T}{\partial X_{\alpha-90}}$$

where superscripts (a) refer to anomalies, $T_{ET}^{(a)}(\alpha)$ represents the temperature anomalies found in the Ekman layer for a wind stress applied in the direction α , $U_{E\alpha}^{(a)}$ the Ekman transport anomalies associated with it, $\frac{\partial T}{\partial X_{\alpha-90}}$ the horizontal temperature gradient in the direction $\alpha - 90^\circ$ (positive angles counterclockwise).

Taking the time derivative into account, the equation of motion in the Ekman layer becomes:

$$\frac{\partial \vec{U}_E}{\partial t} + f \vec{k} \times \vec{U}_E = \frac{1}{\rho} \vec{\tau}$$

and we can expect slightly different behaviors than in the case of steady motion. Especially, considering an oscillatory wind stress applied at the surface of the ocean $\vec{\tau} = \vec{\tau}_a e^{i\omega t}$ and looking for solutions with the same frequency $\vec{U}_E = \vec{U}_{Ea} e^{i\omega t}$, the equation becomes:

$$i\omega \vec{U}_{Ea} + f \vec{k} \times \vec{U}_{Ea} = \frac{1}{\rho} \vec{\tau}_a$$

and we can expect a phase shift between the Ekman transport and the applied wind stress.

We studied the effect of an applied wind stress over Line-P in the zonal and the meridional directions. Anomalies are calculated for the region $[47.5^\circ\text{N}; 52.5^\circ\text{N}] \times [125^\circ\text{W}; 145^\circ\text{W}]$. The first three PCs used for the CCA are calculated for the same period as for Line-P data (May 1956 - September 2002).

3.1.1.1 Zonal wind stress anomalies

Results The highest correlation is found for Line-P temperature anomalies lagging wind stress anomalies by 2 months (Figure 3.1a). This peak in correlation around zero-lag indicates that the two signals are significantly correlated, which is also confirmed by the test (see Table in Figure 3.1). The forcing CCA spatial pattern (Figure 3.1b) indicates positive zonal (ie westerly) wind stress anomalies over the whole domain with a strong gradient in the offshore direction. The Line-P CCA spatial pattern (Figure 3.1c)

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+2	76.8%	12.4%	0.50	0.47	99.2%

Figure 3.1: CCA between 3 PCs of zonal wind stress anomalies over Line-P ($[47.5^{\circ}\text{N}; 52.5^{\circ}\text{N}] \times [125^{\circ}\text{W}; 145^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. **a)** CCA correlations with lags; **b)** Forcing CCA spatial pattern; **c)** Line-P CCA spatial pattern; **d)** Standardized CCA temporal coefficients with the five-year running means, for the forcing CCA mode (top) and the Line-P CCA mode (bottom) (year ticks correspond to January for the Line-P mode time series). The table gives the **lag** considered; **Variance explained 1** is the variance explained by the forcing CCA mode, **Variance explained 2** by Line-P CCA mode; **Correlation 1** is the CCA correlation (5-year running mean removed from CCA-input variables), **Correlation 2** is the correlation between the two CCA modes shown in d) (all frequencies included); **Significance test** is the percentage of random CCA giving a lower correlation than correlation 1.

Figure 3.2: Mean (a) meridional and (b) zonal surface temperature gradient along Line-P.

consists of negative temperature anomalies concentrated in the upper layer and spread all along Line-P. Their strength decreases regularly with depth and are almost null around 150 m. At station 1, very strong anomalies are present up to 100 meter-depth. The correlation of the two time series is lower when the long-term variations are added. The Line-P mode has a strong low-frequency signal, contrary to the forcing CCA time series (Figure 3.1d).

Discussion The negative sign of the Line-P surface temperature anomalies associated with positive zonal wind stress anomalies is consistent with anomalous advection of cooler water from the north as expected from Ekman theory. Nevertheless, strong variations in the magnitude of the forcing anomalies along Line-P do not correspond to similar strength variability of surface temperature anomalies. In fact, for a given zonal wind stress anomaly over Line-P, the surface temperature anomalies should be greater in the case of a stronger mean meridional temperature gradient. We assume that the typical meridional surface temperature gradient may be decreasing in strength inversely to the applied zonal wind stress anomalies in the offshore direction.

We averaged long-term mean (Levitus) ocean temperature from the surface to 20 m depth and derived the meridional temperature gradients. In Figure 3.2a, the mean meridional surface temperature gradient consists of the average of the derived meridional gradients from 47.5°N to 51.5°N and from minus one degree to plus one degree around the given longitude. The gradient gets weaker (absolute value) from the coast to around 134°W, from -4.5 to nearly $-2.5^{\circ}\text{C}/1000\text{ km}$. From 134°W to 145°W, there is a slight trend towards stronger gradients. From the coast to 135°W, the strong increase in zonal wind stress anomalies (Figure 3.1b) is associated with a significant decrease in the strength of the meridional surface temperature gradient. From 135°W to 145°W, the two fields are almost constant in magnitude. This relationship is consistent with the weak spatial variability of surface temperature anomalies observed along Line-P. The depth over which large temperature anomalies occur (around 100 m depth) is consistent with typical Ekman layer depth, usually thought to be between 10 and 100 m deep (Gill, 1982, sec. 9.1).

For station 1, the strong negative temperature anomalies indicate upwelling anomalies. As the coast of Vancouver Island is roughly directed northwestward, the wind stress anomalies in the zonal direction can effectively lead to upwelling-related phenomena. Also, this u-wind (stress) pattern must be associated with a pattern for v-wind (stress) since those two variables are directly related through the conservation of mass. There must be either strong southward or northward winds at the coast associated with the decrease of the zonal wind in the x-direction. The strong capture of upwelling anomalies suggests that an anomalous southward wind at the coast is also associated with the mode.

The highest CCA correlation found for a lag of +2 months may indicate a phase shift between the wind stress and the resulting Ekman transport due to forcing oscillations corresponding to non-steady conditions (see *Physics* part). The long-term variations of the Line-P time series, not associated with the forcing ones, indicate that another mechanism influences the low-frequency variability of surface temperature along Line-P.

3.1.1.2 Meridional wind stress anomalies

The results for meridional wind stress anomalies are shown in Figure 3.3.

Results A peak in correlation appears for a lag of +1 month. The significance test indicates the relevance of this correlation. The forcing CCA spatial pattern indicates positive anomalies over the whole domain, with the strongest ones being found between 130°W and 135°W. The corresponding Line-P CCA pattern consists of weak negative surface temperature anomalies farther than 400 km along Line-P (west of 130°W)

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+1	47.2%	12.4%	0.45	0.37	94.0%

Figure 3.3: CCA between 3 PCs of meridional wind stress anomalies over Line-P ($[47.5^{\circ}\text{N}; 52.5^{\circ}\text{N}] \times [125^{\circ}\text{W}; 145^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

and strong nearshore positive anomalies. The offshore anomalies are concentrated in the upper 40 m and are slightly stronger after 800 km along Line-P (west of 136°W). The nearshore anomalies extend down to 100 m depth and are centered 100 km from station 1 at approximately 30 m depth. The two time-series are not well correlated for the long-term variations, as indicated by a weaker correlation when those ones are considered. The low-frequency signal is large for the Line-P mode, not for the forcing time series.

Discussion From Ekman theory (see Section 3.1.1), the meridional wind stress anomalies are expected to induce a zonal transport. To interpret the surface temperature anomalies observed in the Line-P CCA mode, we calculated the mean zonal surface temperature gradient along Line-P. We averaged the zonal surface temperature gradients (derived from climatological (Levitus) ocean temperature averaged from 0 to 20 m) over the domain $[47.5^\circ\text{N}; 51.5^\circ\text{N}] \times [(L - 2^\circ\text{W}); (L + 2^\circ\text{W})]$, where L refers to the longitude being considered. Figure 3.2b shows the results. From around 130°W to 145°W, the zonal temperature gradient is positive, associated with warmer temperature in the eastward direction. Positive meridional wind stress anomalies are expected to result in anomalous eastward transport, leading to negative temperature anomalies for this section of Line-P. This is what is observed for the Line-P CCA spatial pattern. The strongest forcing anomalies found between 130°W and 135°W are associated with moderate zonal temperature gradients, compared to farther offshore, which can explain the small variability of the surface anomalies. East of 129°W, the zonal surface temperature gradient is negative, and positive meridional wind stress anomalies should lead to positive surface temperature anomalies, as is actually observed. The location of the transition between negative and positive temperature anomalies around 400 km along Line-P is well explained by the change in the sign of the mean zonal temperature gradient.

Close to the coast, the temperature anomalies result from a coastal effect of the wind stress. Meridional wind stress along the coast results in downwelling anomalies, which influence the coastal currents. This effect is studied in more detail in Section 3.1.4.

The lag of +1 month found to give the highest correlation may indicate a phase shift in the response of the ocean to the oscillatory wind stress. The long-term variations of Line-P time series are not associated with the corresponding forcing oscillation, suggesting that the mode also captures variability associated with another process.

Figure 3.4: Highest CCA correlations found between 0 and 3-month lag (Line-P anomalies lagging) for different powers of the wind speed.

3.1.2 Wind mixing anomalies

Physics Wind speed affects the mixing of the ocean surface layer. Turbulent mixing theory gives the depth of the mixed layer as a cubic function of the wind speed.

In the Gulf of Alaska, the surface layer is usually warmer than the deeper layer, so that strong mixing cools the surface layer. Positive wind speed anomalies are expected to be associated with negative temperature anomalies in the surface layer, which is also deepened, hence positive temperature anomalies are also expected in the deepest part of the mixed layer.

Power consideration To test if we can get higher correlations for wind speed cube anomalies, we considered the highest CCA correlation between 0 and 3-month lag for different powers of the wind speed. Results are shown in Figure 3.4. The correlation is almost constant for values of the power between 0.2 and 1, then decreases regularly. We cannot detect the cubic relationship. This in fact may indicate an increasing influence of noise. Our wind speed time series contains noise and approximations, some of it inherent to averages performed (coarse spatial resolution, monthly values, three-month running mean). We suspect that with increasing powers, the imperfections get amplified compared to the true signal, which results in lower correlations. Hence we will only consider anomalies of the wind speed, i.e. for the power equal to 1.

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+2	47.6%	12.1%	0.46	0.42	95.1%

Figure 3.5: CCA between 3 PCs of wind speed anomalies over Line-P ($[47.5^{\circ}\text{N}; 52.5^{\circ}\text{N}] \times [125^{\circ}\text{W}; 145^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

Results A peak in correlation occurs for a lag of +2 months (Figure 3.5a). The test confirms that the correlation is significant. The forcing CCA spatial pattern consists of positive anomalies centered around 140°W south of Line-P. Close to the coast (East of 130°W), the wind speed anomalies are very weak. For the Line-P CCA spatial pattern, the temperature anomalies appear at the surface all along Line-P. In the far offshore section (farther than 1100 km along Line-P), the surface variability is the strongest of all and anomalies extend down to 100 m with a relatively smooth decrease. In the intermediate section (300 to 1100 km along Line-P), the anomalies are concentrated in the upper 40 m and the transition between strong surface and weak deeper variability is sharp. The nearshore section (0 to 300 km) has weak anomalies near the surface. The two time series are not correlated for the long-term variations, which is attested to by a lower correlation when these are considered. In fact, the Line-P time series contains an interdecadal oscillation, contrary to the forcing temporal coefficient.

Discussion The negative sign of the surface anomalies associated with positive wind speed anomalies is coherent with an enhanced wind mixing of the surface layer with colder deeper water. The variation in the strength of the surface temperature anomalies is also consistent with the variations of the strength of the overlying wind speed anomalies. The strongest ones are found far offshore and the anomalies are very weak for the nearshore domain.

The negative anomalies due to an anomalously strong wind mixing are expected to take place within the mixed layer. The different depths of the anomalies in the three domains tend to indicate different typical mixed layer depths. For L ranging from 125.5°W to 145.5°W, we averaged the long-term monthly mean mixed layer depth (Levitus) over the domain $[47.5^\circ\text{N}; 51.5^\circ\text{N}] \times [(L - 1^\circ\text{W}); (L + 1^\circ\text{W})]$. We then calculated the climatological mean (average of monthly means) and the corresponding standard deviations (Figure 3.6). The nearshore near-surface anomalies indeed correspond to shallow mixed layer depths. Far offshore (farther than 1100 km along Line-P or west of 140°W), the depth of the strongest temperature anomalies (around 50 m) also correspond to the mean mixed layer depth. Weaker anomalies found down to 100 m are consistent with anomalous wind mixing occurring during months of deeper mixed layer. For the intermediate section, the uniform depth of temperature anomalies found in Figure 3.5c (40 m) is not clearly related to a uniform typical mixed layer depth (Figure 3.6).

We do not observe positive temperature anomalies underlying the surface negative ones as a result of an anomalously deep mixed layer (see *Physics* part). Our analysis is unable to resolve such fine observations. Also, since the study is performed for all months of the year, associated with different mixed layer depths,

Figure 3.6: Climatological mean mixed layer depths along Line-P with standard deviations derived from seasonal variations.

anomalously strong wind mixing will result in positive temperature anomalies underlying shallow mixed layer depth during low wind speed months and negative temperature anomalies at the same depth for months associated with deeper mixed layers. This mixed effect is expected to mask fine observations around the deepest part of the mixed layer at a given location along Line-P.

The long-term variations of the Line-P CCA time series, not associated with the forcing ones, suggest that the mode also captures another variability.

3.1.3 Ekman pumping and Sverdrup balance anomalies

Physics

Ekman pumping Spatial variations in the wind stress lead to spatial variations in the Ekman transport. This implies zones of divergence or convergence in the Ekman layer. Assuming a flat surface and slow variations in the wind stress so that local balance according to Ekman transport theory can be established, it can be shown that vertical velocity in the Ekman layer is expected to be related to the curl of the wind stress (Gill, 1982, sec. 9.4) by

$$w_{EP} = \frac{1}{\rho} (\nabla \times \frac{\vec{\tau}}{f}) \cdot \vec{k}$$

This process is called Ekman pumping. For Line-P, f can be considered constant. According to this theory, positive anomalies of the curl of the wind stress will raise the pycnocline and thermocline. In the Gulf of Alaska where surface waters are usually warmer at the surface than in the underlying waters, positive anomalies in the curl of the wind stress should be associated with negative temperature anomalies in the surface layer. An indication of the strength of those anomalies is given by

$$T_{EP}^{(a)} \propto w_{EP}^{(a)} (T_d - T_s)$$

where superscripts (a) refer to anomalies, $T_{EP}^{(a)}$ to the temperature anomalies in the surface layer, and T_s and T_d to the typical temperature in the surface layer and for the deeper subsurface water, respectively. The surface layer can be expected to be the mixed layer where temperature is approximately homogeneous and different from the deeper layer, in a simple two-layer model, even if the horizontal motion resulting from Ekman transport affects the Ekman layer.

Sverdrup balance The curl of the wind stress is also associated with the Sverdrup balance. Considering a domain large enough so that the β -effect applies, where the relative vorticity can be neglected compared to the planetary vorticity and for which the general assumptions presented in Section 3.1.1 can be used, we expect a north-south advection following

$$V_{Sv} = \frac{1}{\rho\beta} (\vec{\nabla} \times \vec{\tau}) \cdot \vec{k}$$

where V_{Sv} is the vertical integral of northward velocity (Gill, 1982, sec. 11.13). This motion is expected to extend very deep, down to 500-1000 m.

The hypotheses typically apply in the case of open ocean and are reasonable assumptions for the Gulf of Alaska and along Line-P; the North Pacific Drift is indeed very steady with low relative vorticity. Following this theory, temperature anomalies should be related to anomalies of the curl of the wind stress and to the typical meridional temperature gradient:

$$T_{Sv}^{(a)} \propto -V_{Sv}^{(a)} \frac{\partial T}{\partial y}$$

Three PCs of wind stress curl anomalies are used in order to account for both Ekman pumping and Sverdrup balance processes.

Results Figure 3.7a shows a peak in correlation for a lag of 2 months. 83.6% of the random CCAs gave lower correlations, which indicates the weak significance of the results. The forcing CCA spatial pattern shows two regions of negative and positive wind stress curl anomalies west and east of 130°W over Line-P, respectively. The corresponding spatial pattern for Line-P indicates negative surface temperature anomalies farther than 300 km along Line-P and weak positive ones closer to the coast. For the far offshore section (farther than around 1100 km along Line-P), the surface anomalies are the strongest of all and the negative anomalies decrease smoothly down to 100 m depth. For the intermediate domain, anomalies are concentrated in the upper 40 m and the transition is sharp toward the deeper low variability. For the nearshore domain, the positive anomalies are weak, with a center at 100 km along Line-P, between 30 and 50 m depth. The temporal coefficients are not correlated in the low-frequencies. The long-term oscillations are much greater for the Line-P mode time series than for the forcing ones.

Discussion Positive wind stress curl anomalies are expected to result both in anomalous upwelling through Ekman pumping and in an anomalous northward current through Sverdrup balance. In the first case, negative surface temperatures are expected; positive ones in the second. Our results would be consistent with a dominant effect of Sverdrup balance over Ekman pumping, with positive surface temperature anomalies overlying positive wind stress curl anomalies over the nearshore domain, and inversely farther offshore. Nevertheless, the temperature anomalies are only found at the surface, which is not consistent with the Sverdrup motion, expected to extend deeper. The Line-P CCA mode may in fact represent the variability of another forcing mechanism not directly related to wind stress curl anomalies. It is also suggested by the low value of the significance test.

3.1.4 Upwelling and downwelling anomalies

Physics Close to the coast, Ekman transport can have different impacts. Wind blowing along the coast will lead to an Ekman transport perpendicular to it. Surface waters pushed toward the coast will accumulate and extend deeply, whereas surface waters driven offshore will be replaced by deeper waters at the coast. The first case is called downwelling, the second one upwelling. The typical length scale of influence is of the order of tens of kilometers from the coast (Gill, 1982, sec. 10.11).

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+2	21.5%	13.0%	0.43	0.39	83.6%

Figure 3.7: CCA between 3 PCs of wind stress curl anomalies over Line-P ($[47.5^{\circ}\text{N}; 52.5^{\circ}\text{N}] \times [125^{\circ}\text{W}; 145^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

Off the coast of Vancouver Island where the first stations of Line-P are, positive upwelling rate anomalies will bring colder and more saline waters to shallower depths, eventually up to the surface. The contrary can be expected for downwelling anomalies. Coastal-water temperature anomalies should be related to the alongshore wind stress anomalies. The relationship may not be linear or the same at different locations and depths. For example, in an already downwelling context, downwelling anomalies may not lead to warmer temperature in the surface layer if no surface temperature gradient exists perpendicular to the coast, but positive temperature anomalies may be found at some depth, associated with the deeper accumulation of surface waters.

Also, another effect expected by northward alongshore wind stress anomalies along the coast of North America is northward advection anomalies for the coastal current, and also for the broader currents found hundreds of kilometers from the coast. In the first case, the accumulation of warmer and fresher water (hence less dense) at the coast will enhance the density gradient in the cross-shore direction and resulting in a stronger northward coastal current through geostrophic balance. For the broader and farther offshore currents (California Current along the west coast of Mexico and the U.S. or the Alaska Current along the eastern part of the Gulf of Alaska), the accumulation of warmer water over the continental shelf by northward alongshore wind stress anomalies will also lead to northward current anomalies. Northward current anomalies themselves will lead to anomalous advection of coastal waters from the south, which are usually warmer, resulting in positive temperature anomalies found at the coast.

Angle consideration In order to study upwelling-related phenomena, we considered the wind stress anomalies off the coast of Vancouver Island for different angles departing from the alongshore direction. The response along Line-P may be greater for slightly different angles than the straight alongshore wind stress component. The multiple averages and imperfections of the data sets, as well as the simplifications used in Ekman transport theory, may not lead to oceanic transports exactly 90° to the right of the applied wind stresses.

We calculated the components of the wind stress parallel and perpendicular to the coast at 47.5°N and 50°N , at three longitude points surrounding the coast ($[122.5^\circ\text{W}; 125^\circ\text{W}; 127.5^\circ\text{W}]$ and $[125^\circ\text{W}; 127.5^\circ\text{W}; 130^\circ\text{W}]$, respectively), with an inclination of the coast estimated to 20° and 50° counterclockwise, respectively (see Figure 3.8). The two perpendicular components were then used to calculate the component of the wind stress at any angle α away from the alongshore direction. All the anomalies of the components were then averaged to represent the time series for the wind stress anomalies in the direction α . To determine the

Figure 3.8: Map showing the locations and the directions of the alongshore wind stress used to get the alongshore wind stress anomaly time series.

Figure 3.9: Highest CCA correlations found between 0 and 3-month lags (Line-P anomalies lagging) for CCA between 9 PCs of Line-P temperature anomalies and the wind stress anomalies applied in the alongshore direction rotated counterclockwise by an angle α .

highest response depending on the angle departing from the coast, we considered the highest CCA correlation found between 0 and 3-month lags for different angles. In Figure 3.9, $\alpha = 0^\circ$ corresponds to alongshore wind stress anomalies, $\alpha = 90^\circ$ or $\alpha = -90^\circ$ represents the component of the wind stress anomalies perpendicular to the coast, pointing offshore in the first case, inshore in the second.

The greatest temperature sensitivity along Line-P is found for an angle $\alpha = 15^\circ$ counterclockwise from the alongshore direction. The CCA results for this angle are shown in Figure 3.10.

Results The test indicates a significant correlation at +1 month, where we find the highest correlation. As expected, the main variability occurs at the coast. Two main positive anomaly centers are found down to 100 m at station 1, and around 30 m depth at station 3 (87 km along Line-P and 70 km from the coast (Table 6.1 in Appendix 1)). The temperature anomalies decrease down to 300 m along the continental slope, and farther offshore to a little beyond 100 m. Line-P time series contains strong low-frequency signals compared to the forcing, but the long-term oscillations are synchronized for most periods between the two.

Discussion Positive coastal temperature anomalies associated with the northward alongshore wind stress ones is consistent with the expected influence. We clearly see upwelling-related phenomena from the deep

Lag (month)	Correlation 1	Correlation 2	Variance explained	Significance test
+1	0.49	0.49	12.03 %	98.7 %

Figure 3.10: CCA between wind stress anomalies 15° counterclockwise from the alongshore direction and 9 PCs of Line-P temperature anomalies. **a)** CCA correlations with lags; **b)** Line-P CCA spatial pattern; **c)** Standardized temporal coefficients with the five-year running means, for the forcing time series (top) and the Line-P CCA mode (bottom) (year ticks correspond to January for the Line-P mode time series). The table gives the **lag** considered; **Variance explained** is the variance explained by the Line-P CCA mode; **Correlation 1** is the CCA correlation (5-year running mean removed from CCA-input variables), **Correlation 2** is the correlation between the two time series shown in c) (all frequencies included); **Significance test** is the percentage of random CCA giving a lower correlation than correlation 1.

strong anomalies found at Station 1, by accumulation of surface warm water at the coast and enhanced northward coastal current. The broader variability, centered at station 3 correspond to northward advection anomalies for the broader coastal current.

The long-term variability of the mode is not completely explained by the forcing time series. The mode is significantly related to the alongshore wind stress anomalies in its high-frequencies (of order several months), but Line-P CCA mode contains interdecadal oscillations not entirely accounted for by this process for its interdecadal oscillations.

3.1.5 Heat flux anomalies

Physics Temperature differences between the atmosphere and the underlying ocean result in a transfer of heat called the sensible heat flux. Also, differences in specific humidity between the surface of the ocean and a standard level above result in a latent heat flux due to evaporation. For both transfers, positive net flux anomalies (directed upward) are expected to result in negative sea surface anomalies corresponding to enhanced heat loss or reduced heat gain, and inversely for negative flux anomalies.

The study of heat transfers are performed using 3 PCs of sensible and latent heat net flux anomalies over the domain $[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$.

3.1.5.1 Sensible heat net flux anomalies

Results Figure 3.11 shows the results for the study of the influence of sensible heat flux anomalies on Line-P temperature anomalies. The highest correlation is found for a lag of +1 month and is weak significant according to the test (84.6%). Also, the forcing spatial pattern indicates that the main variability is very localized (46.67°N , 127.5°W) and that only weak anomalies overly Line-P. It suggests that the results do not correspond to a direct effect of the forcing considered.

3.1.5.2 Latent heat net flux anomalies

Results The results of the study performed with 3 PCs of latent heat net flux anomalies are shown in Figure 3.12. The highest CCA correlation found around zero lag is for a delay of +1 month. Nevertheless, the value of this correlation is very low and is similar to the ones found for different lags, even large. It indicates a weak significance of the correlation, which is also attested by a low value of the test (84.9%).

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+1	30.8%	12.3%	0.39	0.24	84.6%

Figure 3.11: CCA between 3 PCs of sensible heat net flux anomalies over Line-P ($[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+1	37.2%	13.3%	0.39	0.37	84.9%

Figure 3.12: CCA between 3 PCs of latent heat net flux anomalies over Line-P ($[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

3.1.6 Radiation effects

Physics Solar radiation is peaked in the visible spectrum with relatively short wavelengths. When propagating through the atmosphere, part of it is absorbed (mainly by O_3 , O_2 and H_2O molecules), another part is reflected or scattered by aerosols and the rest reaches the surface. A part of the latter will also be reflected from the surface, depending on the angle of incidence and the surface roughness, which is related to the wind speed in the case of the ocean. The remaining part of the radiation, which is absorbed near the surface contributes to its warming.

Also, the ocean emits long-wave radiation. This outgoing radiation is strongly absorbed and scattered by the atmosphere due to its greenhouse gases (mainly H_2O). Clouds also contribute to this absorption and to reflection. The reflection and the reemission of long-wave radiation by the atmosphere and the clouds constitute a back radiation that is redirected towards the surface.

For short-wave solar radiation and long-wave back radiation, clouds, atmospheric gases and aerosols have important effects on what is absorbed by the surface. For a cloud, this influence on short-wave or long-wave radiation depends on its type and height. For solar radiation, presence of clouds will mainly result in less radiation reaching the surface and consequently less radiative warming, whereas the effect will be opposite for long-wave radiation. Also, for solar radiation, higher concentration of gases and aerosols in the atmosphere is expected to mainly result in a cooling of the surface since more incoming radiation is absorbed or scattered. Indeed, even if the atmospheric molecules re-emit part of the absorbed solar radiation, energy is lost for the warming of the atmosphere and the emission is not entirely directed towards the surface as for solar radiation. For long-wave radiation, more surface warming is expected with more absorption since it leads to more back radiation.

3.1.6.1 Clear sky downward solar flux anomalies at sea level

Clear sky downward solar flux (CSDSF) anomalies at sea level indicate anomalies in the physical properties of the atmosphere. The variations of solar flux reaching the surface depends on the variations of concentration of some gases (mainly O_3 , O_2 and H_2O) and aerosols interacting with it in the atmosphere. The three PCs of CSDSF anomalies are obtained on the domain $[46.67^\circ N; 52.38^\circ N] \times [123.75^\circ W; 146.25^\circ W]$. Results are shown in Figure 3.13.

Results A clear peak is found for a lag of +1 month, which corresponds to a significant correlation. The forcing CCA spatial pattern indicates positive CSDSF anomalies all over the domain overlying Line-P,

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+1	42.0%	12.5%	0.46	0.43	91.1%

Figure 3.13: CCA between 3 PCs of clear sky downward solar flux anomalies over Line-P ($[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

strengthening eastward. The Line-P corresponding spatial pattern shows negative temperature anomalies mostly concentrated at the surface in the nearshore domain (0 to 300 km along Line-P). Weak negative anomalies also extend 900 km along Line-P and down to around 200 m depth. The forcing temporal coefficient has weak low-frequency oscillations, unlike the Line-P time series.

Discussion The strength of the forcing and Line-P temperature anomalies have the same spatial distribution, which could indicate a direct relationship. Nevertheless, we would expect positive CSDSF anomalies, which means more solar flux reaching the surface, to be associated with a warming of the surface waters, hence positive SST anomalies. The opposite effect is observed. The results of the CCA do not correspond to a direct effect of the phenomena we wanted to consider.

3.1.6.2 Clear sky downward long-wave flux anomalies at sea level

The results for the clear sky downward long-wave flux (CSDLF) anomalies at sea level as the forcing time series are shown in Figure 3.14. It is expected to indicate back radiation anomalies due to anomalous concentration of greenhouse gases (mainly H_2O) in the atmosphere.

Results The highest CCA correlation is found between 0 and +1 month lag. The forcing CCA pattern consists of positive CSDLF anomalies for the whole domain. Over Line-P, the values are quite uniform with slightly greater ones close to the coast and around $135^\circ W$ (700 km along Line-P). The Line-P mode shows positive temperature anomalies in the upper 40 m for the intermediate section, stronger and deeper ones farther offshore, and weak near-surface anomalies nearshore. The interdecadal oscillations of the two modes are highly correlated.

Discussion The sign of the anomalies are consistent in both patterns, more long-wave radiation reaching the surface being expected to anomalously heat the surface and lead to positive surface temperature anomalies. Nevertheless, the spatial distribution of the strength of the anomalies does not match for the two patterns. CSDLF anomalies are quite uniform over Line-P, whereas there is a strong increase in the strength of Line-P SST anomalies westward. The Line-P CCA mode seems more influenced by another parameter that would better explain the spatial variability of the strength of the temperature anomalies.

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
0	59.3%	13.6%	0.62	0.66	100%

Figure 3.14: CCA between 3 PCs of clear sky downward long-wave flux anomalies over Line-P ($[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

3.1.6.3 Cloud forcing net solar flux anomalies

Cloud forcing net solar flux (CFNSF) is the difference between the clear sky net solar flux (CSNSF) and the actual one (NSF): $CFNSF = CSNSF - NSF$. It gives negative values which indicate that less radiation reaches the surface during cloudy conditions. Positive CFNSF anomalies are associated with less cloud effects and more incident radiation reaching the surface. Hence, we expect positive CFNSF anomalies to lead to positive SST anomalies. Results obtained using 3 PCs of those forcing anomalies over the domain $[46.67^\circ\text{N}; 52.38^\circ\text{N}] \times [123.75^\circ\text{W}; 146.25^\circ\text{W}]$ are shown in Figure 3.15.

Results A peak in correlation is found for a lag of +1 month, nevertheless, the test (67.3%) suggests a low significance of the results. Also, the spatial patterns do not match. The results do not correspond to a direct influence of the forcing studied.

3.1.6.4 Cloud forcing net long-wave flux anomalies

Cloud forcing net long-wave flux (CFNLF) represents the difference between the clear sky net long-wave flux (CSNLF) and the actual one (NLF): $CFNLF = CSNLF - NLF$. It gives positive values, and positive anomalies are associated with more back radiation reaching the surface, mainly through cloud re-emission. We therefore expect positive CFNLF anomalies to result in positive surface temperature anomalies. The results of the CCA are shown in Figure 3.16.

Results The highest correlation is found for no lag. The forcing spatial pattern consists of positive anomalies over the whole domain with the strongest values found southeast of Line-P, and the weakest ones southwest of Line-P. Over the line, positive CFNLF anomalies decrease in strength in the offshore direction. The Line-P mode is similar to the one found for CSDLF anomalies used as a forcing (see Figure 3.14c) except for the sign, with negative surface temperature anomalies down to 40 m for the intermediate domain, stronger ones extending deeper farther offshore (100 m depth) and weak near-surface ones closer to the coast. The long-term oscillations of the two time series do not match.

Discussion Through direct influence of clouds on long-wave flux, we would expect positive sea surface temperature anomalies to be associated with positive CFNLF anomalies, as an indication of more back radiation. As the results observed are opposite in sign, this mode does not correspond to a direct effect of the forcing studied. The two time series are correlated through indirect processes.

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+1	27.1%	12.3%	0.36	0.37	67.3%

Figure 3.15: CCA between 3 PCs of cloud forcing net solar flux anomalies over Line-P ($[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

Lag (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
0	30.1%	12.5%	0.40	0.32	89.5%

Figure 3.16: CCA between 3 PCs of cloud forcing net long-wave flux anomalies over Line-P ($[46.67^{\circ}\text{N}; 52.38^{\circ}\text{N}] \times [123.75^{\circ}\text{W}; 146.25^{\circ}\text{W}]$) and 9 PCs of Line-P temperature anomalies. See Figure 3.1 caption for details.

3.2 Remote influences

3.2.1 Advected temperature anomalies

The North Pacific Current flows eastward in the Line-P region (see Figure 1.1). Temperature anomalies found west of Line-P should be advected eastward along the line. In order to consider the advection of temperature anomalies along the North Pacific Current, we averaged SST anomalies over the domain $[48^{\circ}\text{N}; 52^{\circ}\text{N}] \times [160^{\circ}\text{W}; 170^{\circ}\text{W}]$ and performed the lagged CCA. Results are shown in Figure 3.17.

Results There is one clear peak at 0-1 month lag. The spatial mode consists of positive offshore temperature anomalies concentrated in the upper 40 m and increasingly stronger with distance from the coast, and negative ones for the nearshore domain down to 100 m depth, centered between 30 to 50 m depth. A negative anomaly is also found over the continental shelf. The interdecadal oscillations of the two time series are well synchronized except for the 1990s.

Discussion The peak in correlation being found for no lag, the mode represents temperature anomalies that arise along Line-P at the same time as for the western domain. It does not correspond to an advection of temperature anomalies but only to temperature anomalies caused by the same processes for the two domains. Following Bograd et al. (1999), the magnitude of the eastward surface current is expected to be between 5 cm s^{-1} and 10 cm s^{-1} , or approximately between 130 and $260 \text{ km month}^{-1}$, and slower at deeper depths. From 160°W (Eastern most part of the western domain) to 145°W (western most station along Line-P), the distance is about 1000 kilometers. We estimate that it would take at least 4 months for waters to be advected from the first domain to Line-P. No peaks are found at 4 month-lag nor later.

Eastward advection of temperature anomalies is not significant compared to other mechanisms acting in the region. The North Pacific Current is too slow to advect undisturbed temperature anomalies over thousands of kilometers; other dominant processes act during the drift time.

3.2.2 Coastal propagation

Physics Perturbation of isopycnals or surface height at some places close to the coast of Central and North America will propagate northward along the coast. Both Kelvin waves, a type of the first-class waves (i.e. restored mainly by the action of gravity) and topographic Rossby waves, a type of the second-class waves (restored by variations of f/H), propagate with the coast on their right in the Northern Hemisphere, i.e. northward for the west coast of Central and North America. The coastally-trapped waves are a mixture

Lag (month)	Variance explained	Correlation 1	Correlation 2	Significance test
0	12.29 %	0.44	0.44	83.4 %

Figure 3.17: CCA between SST anomalies averaged over the domain $[48^{\circ}\text{N}; 52^{\circ}\text{N}] \times [160^{\circ}\text{W}; 170^{\circ}\text{W}]$ and 9 PCs of Line-P temperature anomalies. See Figure 3.10 caption for details.

Figure 3.18: Maps showing a) the location (24°N , 112°W) where the SST anomalies off southern Baja California were used for the “coastal propagation” study, and the locations and the directions of the alongshore wind stresses anomalies used for the “California Current anomalies” study (a) and for the “Alaska Current anomalies” study (b).

of these two types of waves. The wave characteristics are difficult to predict and will depend on how strong the stratification is, the exact topography of the continental shelf and slope, the presence of canyons (even if their effects are thought to be small (Codiga, 1999)), and also the wind forcing. Moreover, different wave modes can exist with different ranges of group speeds and wavelengths. A typical offshore length scale has been observed to be of the order of tens of kilometers propagating at speeds of the order of a couple of meters per second (Huyer, 1980; Enfield and Allen, 1980). Also, the variations of f can result in coastally-trapped waves being spread out westward as Rossby waves. We expect coastally-trapped waves to cross Line-P from the south, and temperature anomalies at the coast to be affected by them.

In order to study the propagation of coastal waves, we considered SST anomalies on southern Baja California coast, at 24°N , 112°W (see Figure 3.18a). We chose that remote location following results from earlier studies. Enfield and Allen (1980) and Strub and James (2002b) show that coastal anomalies during El-Niño events are mostly related to atmospheric signals from Northern California to Alaska, compared to oceanic connections further south. We do not want to catch signals due to the same atmospheric process (mainly along-shore wind stress anomalies already studied above) at two different locations along the coast,

but the propagation of coastal waves. We chose southern Baja California coast because winds are thought to be uncorrelated to the ones along southern British Columbia. Results are shown in Figure 3.19.

Results We observe a peak in correlation for a lag of +1 month, highly spread out. The significance test attests the relevance of the correlation. The Line-P CCA spatial pattern is similar to the one found for upwelling-related phenomena (Figure 3.10b) except that the coastal anomalies are spread farther offshore and extend deeper over the continental slope (down to 500 m). Also, anomalies at station 1 are weaker and a strong anomaly center appears at station 5 (233 km along Line-P). Interdecadal oscillations contained in both time series are well correlated.

Discussion The large spreading in the lagged correlation indicates a response spread out in time, consistent with a longer-term influence (several months) of waves propagating at various speeds. The temporal coefficient of the Line-P mode shows slightly more high-frequencies than the predictor time series and may indicate some response to local winds, but the main part of the variance comes from lower-frequencies (interannual periods) as for the forcing time series.

We estimate the alongshore distance from southern Baja California to Vancouver Island to be about 3500 km. The mean group speed of the signal is about 1.3 m.s^{-1} , and corresponds to speeds found by previous studies (Huyer, 1980; Enfield and Allen, 1980).

The structure of temperature anomalies along Line-P looks more like perturbations of the California Current system, with spatial extension from the coast of the order of hundreds of kilometers, than that expected from coastally-trapped waves, which typically extend tens of kilometers from the coast (see *Physics* part). Nevertheless, the signal may start propagating as coastal waves, leading to coastal temperature anomalies which may later detach from the coast according to the dynamics of the California Current System. Also, the location of the SST anomalies used as an input is not at the coast of Southern Baja California but is located farther offshore (see Figure 3.18a).

The long-term oscillations of Line-P mode can be mostly attributed to the forcing studied; as seen in the high correlation at low-frequencies (several months to several years periods).

3.2.3 California Current anomalies

Physics Advection anomalies for the entire California Current can lead to temperature anomalies found along Line-P, as has been suggested as an explanation for the 2002 anomalies (Barth, 2003; Kosro, 2003). Also, these current anomalies seemed to be related to alongshore wind stress (Murphree et al., 2003).

Lag (month)	Variance explained	Correlation 1	Correlation 2	Significance test
+1	13.38 %	0.65	0.66	99.4 %

Figure 3.19: CCA between SST anomalies at $24^{\circ}\text{N}, 112^{\circ}\text{W}$ and 9 PCs of Line-P temperature anomalies. See Figure 3.10 caption for details.

Northward alongshore wind stress anomalies are expected to result in northward advection anomalies for the coastal current found tens of kilometers from the coast and the larger California Current found hundreds of kilometers offshore (see Section 3.1.4). The wind-driven Ekman transport is thought to be a major driving mechanism for eastern boundary currents, even if many other processes can also be influential (Gill, 1982, sec. 10.14).

I averaged the northward alongshore wind stress anomalies along the west coast of the U.S. to represent current anomalies and used it as the input time series for the CCA. The wind stress anomalies have been calculated at [35°N; 120°W], [37.5°N; 122.5°W], [40°N; 125°W], [42.5°N; 125°W] and [45°N; 125°W] in the alongshore direction (40°, 40°, 15°, 0°, and 0° counterclockwise from the northward direction, respectively) (see Figure 3.18a). The results of the CCA are shown in Figure 3.20.

Results A peak in correlation appears for a lag of +1 month, significantly approved by the test. The Line-P CCA spatial pattern indicates strong positive anomalies along station 1 down to 100 m. These anomalies extend westward along Line-P in the upper 100 m with a decreasing strength. Weak anomalies are also observed over the continental slope down to 300 m. The far offshore domain also includes deep moderate positive temperature anomalies. The two time series are not well correlated for the low frequency variations. Line-P mode contains strong interdecadal oscillations contrary to the forcing CCA time series.

Discussion The sign of Line-P temperature anomalies is consistent with northward coastal advection anomalies leading to a displacement of water properties northward, resulting in positive coastal temperature anomalies. The anomalies, centered at the closest station from the shore (Station 1, 35 km offshore), can be explained by an enhancement of the nearshore coastal current, as explained in the *Physics* part. It may also indicate the propagation of wind-forced coastal waves, which are also expected to extend tens of kilometers away from the shore (see Section 3.2.2).

The mismatch between the two CCA time series for low frequencies indicates that the Line-P mode also captures a variability not directed accounted by our proxy representing California Current anomalies.

3.2.4 Alaska Current anomalies

Physics In the same way as the California Current, whose strength anomalies can influence Line-P temperature anomalies, I studied the effect of Alaska Current anomalies on Line-P. Northward alongshore anomalies are expected to result in northward coastal currents anomalies, hence warmer water at the coast. We use northward alongshore wind stress anomalies for the eastern part of the Gulf of Alaska to account

Lag (month)	Variance explained	Correlation 1	Correlation 2	Significance test
+1	11.82 %	0.47	0.46	95.3 %

Figure 3.20: CCA between alongshore wind stress anomalies for the California Current region and 9 PCs of Line-P temperature anomalies. See Figure 3.10 caption for details.

for Alaska Current anomalies in the northward direction. The anomalies are calculated at $[60^{\circ}\text{N}; 145^{\circ}\text{W}]$, $[60^{\circ}\text{N}; 140^{\circ}\text{W}]$, $[57.5^{\circ}\text{N}; 135^{\circ}\text{W}]$, $[55^{\circ}\text{N}; 132.5^{\circ}\text{W}]$ and $[52.5^{\circ}\text{N}; 130^{\circ}\text{W}]$ with directions 90° , 60° , 45° , 40° and 45° counterclockwise from the northward direction, respectively (see Figure 3.18b). They are then averaged to get the proxy time series. Results are shown in Figure 3.21.

Results A small peak in Figure 3.21a is found for a lag of +2 months. The test (85.6%) suggests a weak significance of this correlation. The Line-P spatial pattern shows strong positive temperature anomalies centered at station 3 (87 km along Line-P, 70 km from the closest coast) around 30 m depth. Those positive anomalies extend down to 100 m and around 400 km along Line-P. Farther offshore, negative surface anomalies are found, with a gradient toward stronger anomalies (absolute values) westward. The two time series do not have a similar interdecadal variability.

Discussion Even if the test suggests a weak correlation, I think the Line-P mode has a physical meaning. As we expected, the strongest temperature anomalies are found nearshore and are positive in sign, consistent with northward current anomalies driven by counterclockwise wind stress anomalies along the eastern margin of the Gulf of Alaska.

The offshore negative anomalies indicates that the wind stresses used as an input for the CCA are usually part of typical broad scale atmospheric pressure systems that influences coastal water as well as the center of the Gulf of Alaska. In this section, we wanted to consider only coastal current anomalies; the offshore anomalies are side effects for this study.

Lag (month)	Variance explained	Correlation 1	Correlation 2	Significance test
+2	13.24 %	0.39	0.34	85.6 %

Figure 3.21: CCA between alongshore wind stress anomalies for the Alaska Current region and 9 PCs of Line-P temperature anomalies. See Figure 3.10 caption for details.

Chapter 4

General Discussion

The goal of this section is to draw conclusions concerning the main forcing mechanisms influencing Line-P temperature anomalies with regard to the results found previously.

Most of the results contain features unexplained by a direct influence of the mechanism considered, either for the spatial distribution of the anomalies, or for interdecadal oscillations of the Line-P modes, or for both of them. It means that Line-P temperature anomaly modes capture some variability not directly forced by the forcings studied. Line-P temperature anomalies contain only a few major distinct modes of variability, which can be seen from the occurrence of similar patterns for different forcing mechanisms (Figure 3.5c and 3.7c for example). The overlapping of different processes captured by Line-P modes is not necessarily spurious, since forcing time series can themselves be significantly correlated with one another, resulting in statistically inseparable influences.

In this section, we will consider the different spatial domains along Line-P for which we found specific behaviors, and present the dominant forcing mechanisms for each of them. Those separate domains, which emerged from the observation of the results, are the offshore section of Line-P (farther than 400 km along Line-P), the nearshore section (between 50 and 300 km along Line-P or between 50 and 180 km from shore) and the coastal domain, corresponding to station 1 (35 km offshore). We consider the forcing mechanisms which gave consistent results with the observed temperature anomalies in those sections of Line-P, and determine the dominant ones when it is possible.

4.1 Offshore domain

The only forcing mechanisms for which the offshore temperature anomalies were consistent with the forcing anomalies, were Ekman transport due to zonal and meridional wind stress, and wind mixing. In the case of zonal wind stress anomalies, the strength of the forcing anomalies found over the region and the variability of the mean meridional surface temperature gradient could explain the strength of the observed temperature anomalies. The deepest depth to which temperature anomalies could be found was consistent with an Ekman layer of the order of 100 m (see Section 3.1.1.1). In the case of wind mixing, the strength of wind speed anomalies was strong over the domain, and the depth of the temperature anomalies was consistent with typical mixed layer depths associated with a strong seasonal variation (see Section 3.1.2). For meridional wind stress anomalies, the strength of the observed ocean temperature anomalies was significantly smaller than for the two other studies. Ekman transport anomalies due to meridional wind stress anomalies are influential to a lesser extent.

It may be impossible to know if one of the two supposedly most influential mechanisms (Ekman transport due to zonal wind stress anomalies and wind mixing) has a stronger influence compared to the other one, especially since the two CCA correlations are of the same order (0.50 and 0.46 for zonal wind stress anomalies and for wind speed anomalies, respectively). Also, the correlation between the two forcing CCA time series is significant (0.53), which indicates that the mechanisms partly occur simultaneously, making any statistical attempt to distinguish their roles futile. Nevertheless, the Line-P CCA spatial patterns are different for the entire domain in the two studies (Figure 3.1c and 3.5c), which suggests that the modes do not capture exactly the same variability. Also, since the spatial distribution of the anomalies was consistent with the forcing considered in each case, the two Line-P modes seem to represent the influence of each mechanism over the entire domain, and especially for the offshore section of Line-P.

4.2 Nearshore domain

Nearshore anomalies were significantly strong and consistent with the results expected when the forcing anomalies were derived from zonal and meridional wind stress (Section 3.1.1.1 and 3.1.1.2), wind stress curl (Section 3.1.3), remote coastal temperature (through fast propagating coastal waves, Section 3.2.2), and downwelling favorable wind stress along the coast of Vancouver Island (Section 3.1.4) and along the eastern Gulf of Alaska coast (Section 3.2.4). The influence of zonal and meridional wind stress anomalies over nearshore temperature anomalies is included in the study of upwelling-related phenomena. Also, anomalies

	Downwelling favorable winds	Coastal propagation	Alaska Current
Downwelling favorable winds	1	0.32	0.71
Coastal wave		1	0.12
Alaska Current			1

Table 4.1: Correlations between the forcing CCA time series (without the low frequencies) for the most influential mechanisms on Line-P temperature anomalies in the nearshore section of Line-P. Bold numbers indicate correlations passing the 5% significance level test (t test, see Appendix 3).

found for this domain of Line-P are significantly weaker with wind stress curl anomalies used as a forcing than with the other mechanisms.

The correlations between the remaining forcing CCA modes (Table 4.1) indicate that downwelling favorable wind stress anomalies off Vancouver Island (used for upwelling-related phenomena), and along the eastern margin of the Gulf of Alaska (used for Alaska Current considerations) are highly correlated. Nevertheless, the corresponding Line-P modes were different, especially for the offshore domains and for the depth extension of temperature anomalies at the coast (Figure 3.10b and 3.21b). Moreover, the optimal timing of the signals was found to be +1 month in the first case, +2 in the second, which also suggest a specific response captured by the Line-P modes in each case. The time series used to represent coastal propagation is weakly correlated to the two other forcing mechanisms. We would expect a distinct Line-P spatial pattern associated with this time series. In fact, the CCA Line-P spatial patterns are similar in the case of the coastal propagation and upwelling studies (Figure 3.10b and 3.19b), but since they can be both explained by the forcing mechanism considered, this similarity may not indicate that one of the results is spurious. The significance of both results is also suggested by the fact that the upwelling anomalies seem to explain the highest frequencies of the Line-P mode (few months periods, see Figure 3.10c), whereas the coastal propagation of temperature anomalies explains the lowest ones (interannual to interdecadal periods, see Figure 3.19c). We conclude that the dominant mechanisms responsible for temperature anomalies approximately between 50 and 180 km from the coast are upwelling-related phenomena (wind stress anomalies along Vancouver Island coast), the propagation of temperature anomalies along the coast through oceanic connections and anomalies in the strength of the Alaska Current.

4.3 Coastal domain

At station 1, strong temperature anomalies were found in the case of zonal and meridional wind stress anomalies (Section 3.1.1.1 and 3.1.1.2), downwelling favorable wind stress along the coast of Vancouver

Figure 4.1: 8 CCA correlations with lags for CCAs between 9 PCs of Line-P temperature anomalies and 8 PCs of SLP anomalies over the domain $[20^{\circ}\text{N}; 80^{\circ}\text{N}] \times [110^{\circ}\text{W}; 180^{\circ}\text{W}]$.

Island (Section 3.1.4), coastal propagation of temperature anomalies (Section 3.2.2), and anomalies in the strength of the California Current (Section 3.2.3). The influence of zonal and meridional wind stress anomalies were explained by upwelling rate anomalies, whose effects were studied separately. The strength of the temperature anomalies observed at station 1 in the case of oceanic coastal propagation was weaker than for other mechanisms. This process is thought to contribute to a lesser extent to Line-P anomalies at station 1.

For the two remaining most influential mechanisms (downwelling wind and California Current), the role of each of them may be difficult to attest since the forcing CCA time series are significantly correlated to one another (0.70). The temperature anomalies at the coast are mostly influenced by alongshore wind stress anomalies off the coast of Vancouver Island, and by anomalies in the strength of the California Current. Coastally trapped waves are thought to contribute to a lesser extent to those anomalies.

4.4 Broad-scale study

In order to overcome the interdependence of the forcing mechanisms themselves, we studied more general situations encompassing different direct effects through the study of large scale sea level pressure anomaly (SLPA) patterns. For example, a single SLPA pattern over the whole NEP can lead to wind stress anomalies

directly over Line-P (resulting in Ekman transport anomalies), and all along the coast of North America (resulting in upwelling anomalies off Vancouver Island coast, and anomalies in the strength of the Alaska and California Currents). Therefore, we will try to find broad-scale anomalous atmospheric situations that lead to strong temperature anomalies along Line-P. We should also be able to explain the influence of an SLPA pattern on Line-P temperature anomalies by considering its association with the main forcing mechanisms acting on Line-P.

We studied the role of SLP anomaly patterns by performing CCA on the 8 leading PCs of SLP anomalies over the domain $[20^{\circ}\text{N}; 80^{\circ}\text{N}] \times [110^{\circ}\text{W}; 180^{\circ}\text{W}]$ (the first 3 PCs for SLP anomalies are shown in Appendix 4) and the same 9 leading PCs for Line-P temperature anomalies. Figure 4.1 shows the CCA correlations found for the 8 leading modes with different lags.

For the first and the second CCA modes, peaks in correlation are found for a lag of +1 and +2 months, respectively. The corresponding SLPA modes are referred to as SLPA mode 1 and SLPA mode 2 in the following sections. The correlations of other modes do not peak prominently. It suggests that the first two modes are the only ones giving significant results.

4.4.1 First CCA modes

Results

The results for the first CCA modes with a lag of +1 month are shown in Figure 4.2a-b. The Line-P spatial pattern mostly consists of nearshore temperature anomalies. Strong positive anomalies are found for the coastal and nearshore domains (station 1 down to 100 m, and between 50 to 400 km along Line-P with centers around 30 to 40 m). Weak positive anomalies are also found in the intermediate domain (400 to 1100 km along Line-P) between 50 and 100 m. For the far offshore domain (farther than 1100 km along Line-P), moderate positive temperature anomalies are found between the surface and around 100 m depth.

SLPA spatial pattern consists of negative anomalies for the whole domain, centered in the Gulf of Alaska around 54°N , 147°W . Geostrophic wind anomalies associated with this pattern blow counterclockwise in the Gulf of Alaska. Over Line-P, wind anomalies are strong (close isobars) and blowing in the Northeast direction. Over Vancouver Island, the associated wind anomalies are mostly directed perpendicular to the coast.

The two time series are not highly correlated for interdecadal variations. The SLPA mode explains part of the Line-P mode variance in low-frequencies, since similar variations can be observed but the magnitude of those do not match.

Figure 4.2a : First modes for CCA between 8 PCs of SLP anomalies for $[20^{\circ}\text{N}; 80^{\circ}\text{N}] \times [110^{\circ}\text{W}; 180^{\circ}\text{W}]$ and 9 PCs of Line-P temperature anomalies. **i)** CCA correlations with lags; **ii)** Line-P CCA spatial pattern; **iii)** Standardized CCA temporal coefficients with the five-year running means, for the SLPA CCA mode (top) and the Line-P CCA mode (bottom) (year ticks correspond to January for the Line-P mode time series).

Delay (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+1	27.7%	13.1%	0.60	0.59	96.0%

Figure 4.2b : First modes for CCA between 8 PCs of SLP anomalies for $[20^{\circ}\text{N}; 80^{\circ}\text{N}] \times [110^{\circ}\text{W}; 180^{\circ}\text{W}]$ and 9 PCs of Line-P temperature anomalies. SLPA CCA spatial pattern; The table gives the **lag** considered; **Variance explained 1** is the variance explained by the SLPA CCA mode, **Variance explained 2** by Line-P CCA mode; **Correlation 1** is the CCA correlation (5-year running mean removed from CCA input variables), **Correlation 2** is the correlation between the two CCA modes (all frequencies included); **Significance test** is the percentage of random CCA giving a lower correlation than correlation 1.

Discussion

The results suggest that Line-P is predominantly affected by coastal-related mechanisms. Even if the strongest wind anomalies associated with the SLPA pattern are found over Line-P, only small temperature anomalies are found offshore. To understand the influence of the SLPA mode over Line-P temperature anomalies, we consider the correlation between the former and the dominant mechanisms for each section of Line-P. Different lags are considered because two variables may not be exactly synchronous. Also, the previous results indicated different timing for the highest response along Line-P for different forcing mechanisms (between 0 and 2 months). The range of lags considered to find the highest correlation is -3 to +3 months, a positive value corresponding to SLPA pattern lagging the other variable.

Offshore domain For the offshore domain, the two dominant mechanisms responsible for temperature anomalies were found to be through zonal wind stress and wind speed anomalies. For each of these variables, we averaged its anomalies over the domain overlying the offshore section ($[47.5^{\circ}\text{N}; 52.5^{\circ}\text{N}] \times [130^{\circ}\text{W}; 145^{\circ}\text{W}]$) and correlated it with the SLPA mode 1 time series. Results are shown in Table 4.2.

Despite positive zonal wind stress anomalies associated with the SLPA pattern (Figure 4.2b), the correlation found with the average of those anomalies over the offshore section of Line-P gives a significant negative value (-0.43), which means that on average, positive values of SLPA mode 1 time series are associated with negative zonal wind stress anomalies over the offshore domain. Another SLPA mode, not necessarily temporally independent with the mode considered here, may have a stronger influence on zonal wind stress anomalies. Nevertheless, even if SLPA mode 1 is not directly responsible for the forcing anomalies, this negative correlation is consistent with the positive temperature anomalies observed in the offshore domain of Line-P down to 100 m, since it implies that positive values of the SLPA mode 1 are mainly associated with an anomalous northward Ekman transport.

The correlation with mean wind speed anomalies over the offshore domain is insignificant. This forcing is not associated with SLPA mode 1.

The weaker anomalies found at the surface are not fully explained by correlations with the main mechanisms considered.

Nearshore and coastal domains For the nearshore and coastal domains of Line-P, where the strongest temperature anomalies are found, we considered the correlation of SLPA mode 1 with dominant mechanisms influencing this section of Line-P. The variables considered are northward wind stress anomalies along the

a)	Zonal wind stress	Wind speed
Lag (month)	0	0
Correlation	-0.43	0.11

b)	Downwelling favorable wind stress	Coastal propagation	California Current	Alaska Current
Lag (month)	0	0	0	0
Correlation	0.75	0.41	0.70	0.53

Table 4.2: Lags (and corresponding correlations) for which the correlations between SLPA mode 1 and the dominant forcing anomalies are the strongest; for a) offshore mean zonal wind stress and wind speed anomalies; b) downwelling favorable wind stress, coastal propagation, California and Alaska Currents anomalies. Lags considered: -3 to +3 month. A positive lag value correspond to SLPA mode 1 lagging the other variable. Bold numbers indicate correlations passing the 5% significance level test.

coast of Vancouver Island (same time series as in Section 3.1.4), SST anomalies close to the coast of southern Baja California (24°N , 112°W) (see Section 3.2.2) and California and Alaska Currents anomalies, derived from alongshore wind stress anomalies (see Section 3.2.3 and 3.2.4). They are referred as “downwelling favorable wind stress”, “coastal propagation”, “California Current” and “Alaska Current” in Table 4.2.

SLPA mode 1 is highly correlated with mechanisms responsible for nearshore and coastal temperature anomalies. The sign of the correlation is consistent with the expected wind anomalies associated with the SLPA pattern, of which the alongshore components are in the downwelling-favorable direction all along the coast of North America. These correlations explain well the strong positive Line-P temperature anomalies found in the nearshore and coastal domains. All correlations between this SLPA mode and the 4 mechanisms are consistent in sign with the observed Line-P spatial pattern.

Conclusion

SLPA mode 1 is mostly associated with coastal mechanisms. It explains why Line-P temperature anomalies are mostly found in the nearshore and coastal domains of Line-P. Downwelling anomalies off the coast of Vancouver Island push warmer water inshore and trap the fresh water river discharges at the coast, which results in northward coastal current anomalies. Positive northward California and Alaska Currents anomalies also result in more advection of warmer coastal water from the south. Positive sea surface temperature anomalies are also mainly associated with the mode off the coast of Baja California, whose propagation along the coast of North America may be also wind-forced thanks to the northward alongshore wind anomalies along the U.S. West coast. Offshore temperature anomalies are weak and can be explained

by a correlation with negative zonal wind stress anomalies. Nevertheless, the SLPA mode is not directly responsible for the wind anomalies offshore.

4.4.2 Second CCA modes

Results

Figure 4.3a : Second modes for CCA between 8 PCs of SLP anomalies for $[20^{\circ}\text{N}; 80^{\circ}\text{N}] \times [110^{\circ}\text{W}; 180^{\circ}\text{W}]$ and 9 PCs of Line-P temperature anomalies. See Figure 4.2a caption for details.

Delay (month)	Variance explained 1	Variance explained 2	Correlation 1	Correlation 2	Significance test
+2	19.2%	12.8%	0.40	0.33	21.9%

Figure 4.3b : Second modes for CCA between 8 PCs of SLP anomalies for $[20^{\circ}\text{N}; 80^{\circ}\text{N}] \times [110^{\circ}\text{W}; 180^{\circ}\text{W}]$ and 9 PCs of Line-P temperature anomalies. SLPA CCA spatial pattern; The table gives the **lag** considered; **Variance explained 1** is the variance explained by the SLPA CCA mode, **Variance explained 2** by Line-P CCA mode; **Correlation 1** is the CCA correlation (5-year running mean removed from CCA input variables), **Correlation 2** is the correlation between the two CCA modes (all frequencies included); **Significance test** is the percentage of random CCA giving a lower correlation than correlation 1.

The results of the second CCA modes are studied for a lag of +2 months (Figure 4.3a-b). The significance test used in this case consists of the percentage of second modes giving lower correlations than the CCA correlation, derived from 1000 random CCAs. This test is not totally fair since it does not take the first CCA modes results into account. Nevertheless, we think the clear peak found for +2 months is a fair indication of consistent correlation, with the level of random correlation being slightly over 0.3 (correlations between -20 and -5 months for example are expected to have no physical meanings). Also, taking different numbers of SLPA PCs for the study still leads to the capture of this mode, indicating a robust result which does not correspond to simply noise.

The Line-P spatial pattern consists of offshore positive surface temperature anomalies and nearshore negative ones. For the far offshore domain, surface anomalies are the strongest of all, and their strengths decrease smoothly down to 100 m. In the intermediate section, positive surface temperature anomalies are uniformly concentrated in the upper 40 m, with a gradient towards stronger anomalies westward. In the nearshore domain, negative anomalies are also strong and are found in the first 400 kilometers along Line-P. The nearshore anomalies are centered around 40 m depth between 50 and 250 km along Line-P (50 to 150 km from the coast).

The forcing pattern shows strong positive SLP anomalies south of Line-P, centered around 40°N, 145°W and weak negative ones over the Bering Sea and Alaska. The geostrophic anomalous winds associated with it blow clockwise along the coast of the Gulf of Alaska. South of Vancouver Island, the wind anomalies are mostly oriented perpendicular to the coast. Over Line-P, the direction of associated winds is mostly southeastward except the far offshore section and close to the shore, where they are oriented eastward.

The two time series contain strong high-frequency signals (periods of the order of a few months). Line-P mode varies slightly over interdecadal time scales, which is not the case for the SLPA mode.

Discussion

As for SLPA mode 1, we interpret Line-P temperature anomalies associated with SLPA mode 2 by considering correlations of the latter with the dominant forcing parameters influencing Line-P temperature anomalies (same forcing time series as in Section 4.4.1).

Offshore domain Results for the offshore domain are shown in Table 4.3. SLPA mode 2 is significantly associated with negative zonal wind stress and wind speed anomalies over far offshore domain. SLPA mode 2 spatial pattern would imply positive wind anomalies in the zonal direction, hence is not directly responsible

a)	Zonal wind stress	Wind speed
Lag (month)	0	0
Correlation	-0.34	-0.33

b)	Downwelling favorable wind stress	Coastal propagation	California Current	Alaska Current
Lag (month)	0	+2	-1	0
Correlation	-0.08	0.10	0.07	-0.32

Table 4.3: Lags (and corresponding correlations) for which the correlations between SLPA mode 2 and the dominant forcing anomalies are the strongest; for a) offshore mean zonal wind stress or wind speed anomalies; b) downwelling favorable wind stress, coastal propagation, California and Alaska Currents anomalies. Lags considered: -3 to +3 month. Positive lag values correspond to SLPA mode 2 lagging the other variable. Bold numbers indicate correlations passing the 5% significance level test.

for the wind anomalies. These negative correlations are expected to lead to positive temperature anomalies in the offshore domain, which is indeed observed in the Line-P spatial pattern (Figure 4.3aii). Nevertheless, for the intermediate section of Line-P (400 to 1100 km along Line-P), the anomalies are only found in the upper 40 m, which is not consistent with the expected influence of zonal wind stress anomalies in the upper 100 m (expected Ekman layer thickness). The intermediate Line-P section temperature anomalies seem to be mostly related to wind mixing anomalies, especially since weak negative temperature anomalies are found below the positive surface ones (Figure 4.3aii and *Physics* part of Section 3.1.2 for explanation).

Nearshore and coastal domains For the nearshore and coastal domains of Line-P, the correlations between the SLPA mode 2 and the dominant mechanisms controlling temperature anomalies in this section are shown in Table 4.3. The only significant correlation is found for Alaska Current anomalies. The negative sign of the correlation indicates that SLPA mode 2 is usually associated with southward Alaska Current anomalies (in fact southward alongshore wind stress anomalies), which is consistent with the negative temperature anomalies found in the nearshore domain. The SLPA spatial pattern also explains the direction of the anomalous winds found along the eastern margin of the Gulf of Alaska.

Conclusion

The influence of the SLPA mode 2 on temperature anomalies for Line-P offshore domains (west of 130°W) mostly results from weak wind mixing. Westward wind stress anomalies may also be influential for the far offshore domain (west of 140°W). For the nearshore domain, the negative temperature anomalies associated

with SLPA mode 2 are explained by clockwise alongshore wind stress anomalies over the eastern margin of the Gulf of Alaska, which result in southward Alaska Current anomalies.

Chapter 5

Conclusion

The goal of the study which was to sort out minor and dominant mechanisms influencing Line-P temperature anomalies has been reached. Among the mechanisms studied, the ones which are insignificant in determining Line-P temperature anomalies are:

- Wind stress curl related processes (Ekman pumping and Sverdrup balance);
- Sensible heat flux anomalies;
- Latent heat flux anomalies;
- Radiation effects, neither through anomalous atmospheric or cloudiness conditions;
- Advection of temperature anomalies along the North Pacific Current.

Among forcing mechanisms whose effects could be detected along Line-P, their main domains of influence were determined. Over the offshore part of Line-P (west of 130°W or farther than 400 km along Line-P), the two main parameters which influence ocean temperature anomalies are:

- Zonal wind stress anomalies, resulting in meridional Ekman transport anomalies. The Ekman layer is thought to be around 100 m thick;
- Wind speed anomalies, acting through wind mixing processes. The influence was found in the upper 100 m for the far offshore domain of Line-P (west of 140°W or farther than 1100 km along Line-P), in the upper 40 m for the intermediate section (between 400 and 1100 km along Line-P). It may vary depending on the season considered, associated with different mixed layer depth.

Closer to the coast, two main temperature anomaly cells were commonly found; one centered around 30 m depth between 50 and 300 km along Line-P (50 to 180 km from shore), the other one at station 1 (35 km from shore) from the surface to 100 m depth. The first temperature anomaly cell is mostly associated with:

- Alongshore wind stress anomalies along the coast of Vancouver Island (through current induced anomalies): downwelling favorable winds imply an anomalous accumulation of warm (less dense) water over the continental shelf and northward coastal current anomalies;
- Northward propagation along the coast of North America of temperature anomalies from remote southern locations;
- Alaska Current anomalies due to alongshore wind stress anomalies along the eastern margin of the Gulf of Alaska.

The second temperature anomaly cell found at Station 1 mostly appears in the case of:

- Anomalous upwelling (or downwelling), derived from alongshore wind stress anomalies;
- Alongshore wind stress anomalies along California Current System region, which influence the strength of the coastal current and eventually force coastally trapped waves;
- Propagation of remote southern coastal temperature anomalies, but to a lesser extent.

We also found two broad-scale SLPA patterns which significantly influence Line-P temperature anomalies. The first one consists of an anomalously low pressure system centered in the Gulf of Alaska which mostly influences nearshore and coastal sections of Line-P. The effect of this SLPA pattern is explained by an association with downwelling anomalies off Vancouver Island, northward Alaska and California Currents anomalies, and the oceanic propagation of temperature anomalies along the coast of the U.S.. The second SLPA mode consists of a positive sea level pressure cell centered in the middle of the North Pacific Ocean (40°N , 145°W), which results in positive surface temperature anomalies in the offshore part of Line-P, and negative ones closer to the coast. For the offshore domain, the mechanism involved in explaining this influence seem to be through weak wind mixing. At the coast, southward Alaska Current anomalies induced by the SLPA pattern seem to be the only mechanism by which nearshore Line-P water gets colder.

The studies performed to consider the influence of a given mechanism were usually very simple, especially concerning the proxies used to represent the processes. For example, wind stress variables could be improved by considering a drag coefficient varying with the wind speed, which was not the case in this

study. Coastal wave propagation could also be best considered using oceanographic station data along the coast of North America. The California and Alaska Current anomalies that we derived from alongshore wind stress anomalies would be more directly and more accurately considered using Topex-Poseidon data. Nevertheless, the simple proxies used in this study were available for the whole period of Line-P sampling, which made the best statistical use of those data. Also, our study does not take into account seasonal variability. Line-P behavior with respect to a forcing mechanism is expected to change with the period of the year considered, especially since the California Current System has a strong intra-annual variability (Strub and James, 2002a). The processes dominantly acting in the mixed layer may have different influences in months of deep mixed layers (winter) compared to those associated with a shallow mixed layer.

Nevertheless, this simple study gave consistent results, and seemed to be able to consider the individual effects of different mechanisms. Also, further improvements may be limited by statistically inseparable influences through correlated parameters acting through different mechanisms. Similar studies could also be carried out for other oceanographic lines, and potentially at any place around the world using Argo floats data (<http://www.argo.ucsd.edu/>). Those drifters, which now cover most of the world oceans, and which take salinity and temperature profiles could be used to “construct” lines at any location by interpolating Argo data along this line, as is already done by Dr. Freeland along Line-P to extend the data set. Nevertheless, it would require some time to get a data set long enough to perform equivalent statistical analysis.

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Chapter 6

Appendices

Appendix 1: Line-P

Station	Latitude (N)	Longitude (W)	Distance along Line-P (km)	Distance from shore (km)
1	48°34.5'	125°30.0'	0	35
2	48°36.0'	126°00.0'	37	48
3	48°39.0'	126°40.0'	87	70
4	48°44.6'	127°40.0'	161	103
5	48°49.0'	128°40.0'	233	146
6	48°58.2'	130°40.0'	380	225
7	49°07.4'	132°40.0'	526	328
8	49°17.0'	134°40.0'	672	382
9	49°26.0'	136°40.0'	817	474
10	49°34.0'	138°40.0'	961	563
11	49°41.0'	140°40.0'	1106	664
12	49°50.0'	142°40.0'	1250	773
13	50°00.0'	145°00.0'	1420	913

Table 6.1: Locations and distances along Line-P of the 13 stations.

Figure 6.1a : Number of casts performed at each station to get the monthly data for a given month; Stations 1 to 4.

Figure 6.1b : Number of casts performed at each station to get the monthly data for a given month; Stations 5 to 8.

Figure 6.1c : Number of casts performed at each station to get the monthly data for a given month; Stations 9 to 12.

Figure 6.1d : Number of casts performed at each station to get the monthly data for a given month;
Station 13.

Appendix 2: Approximated Principal Component Analysis for Line-P data

Methods

In order to filter the noise from the Line-P data set and to get a few comprehensive time series taking the main variations into account, I performed Principal Component Analysis. Since many data were missing, we had to use approximations to perform the PCA.

In a regular PCA, the spatial patterns are the eigenvectors of the covariance matrix, the eigenvalues giving the variance of the mode and the temporal coefficients (i.e. principal components, PCs) being obtained from the projection of the data points on the eigenvectors. In the method used in this study, the covariance between two spatial points are calculated only from values available for both variables at a given time:

$$c_{ij} = \frac{1}{n'} \sum_k' y_{ik} y_{jk}$$

where c_{ij} is the correlation between the two spatial points referred to as i and j ; k the time index and the prime denotes that the summation only over k for which neither y_{ik} nor y_{jk} is missing, and n' the number of terms in this summation.

Eigenvectors and eigenvalues are then calculated as for a regular Principal Component Analysis. However, initial data points in the original basis (station, depth) often have one or more components missing (e.g. one of the stations not sampled during a specific month), whereas the eigenvectors have components on every axis of the original basis. The projection is only performed in the space of available values, and the eigenvectors, for which not all components are considered, are rescaled to unity (Von Storch and Zwiers, 1999, sec.13.2.8):

$$a_l(t_k) = \frac{\sum_i' e_{li} y_{ik}}{\sum_i' |e_{li}|^2}$$

where a_l and e_l refers to the l^{th} PC and spatial mode, t_k to the time considered, and the superscript primes mean the summations are only over spatial components i for which y_{ik} is not missing.

For months during which no samples had been performed at all, no value for the temporal coefficients can be calculated. We decided to fill in the gaps in the PCs by linearly interpolating from the surrounding values. One can argue that using only the available points would be more precise and rigorous, on the other hand, consecutive values are not totally independent and are correlated to some extent. Interpolation in the case of small gaps or high autocorrelation makes sense. For our data set, the temporal coefficients of the modes consist of 557 points (557 months from May 1956 to September 2002), for which 107 values cannot be calculated. However, most of the gaps only consist of a few missing values (the mean length of the gaps is only 1.5 months with a standard deviation of 0.9 month). In conclusion, it was reasonable to fill in the gaps by interpolation. Moreover, 3-month running averages are also used before performing the CCA, which also increases the degree of autocorrelation.

The variances explained, the spatial modes and the temporal coefficients of the first three Line-P modes are shown in Figure 6.3 for temperature anomalies.

Validity test

To test the results of this approximated PCA, we compared the results of this method performed on the average of temperature anomalies from the surface to 10 meter-depth from the casts, with a regular PCA performed on the NOAA Extended Reconstructed Sea Surface Temperature along Line-P. The latter is performed on the average of temperature anomalies between 48°N and 50°N, from 126°W to 146°W.

If only one cast is used to represent the profile of temperature for a given month, very near surface temperature is highly dependent on the oceanic condition of that particular day and also the time of the day at which the sample is performed. The average from the surface to 10 meter depth is used in order to smooth this variability, and a 3-month running average is performed on all the temporal coefficients obtained (for PCs derived from NOAA Extended Reconstructed SST and from Line-P data).

A comparison of the first four spatial patterns is shown on Figure 6.2. Also Table 6.2 summarizes some characteristics of the four PCA.

	PC1	PC2	PC3	PC4
Variance explained (NOAA SST)	82.89 %	15.61 %	1.20 %	0.24 %
Variance explained (Line-P SST)	53.81 %	22.60 %	6.26 %	5.37 %
Correlation between the temporal coefficients	0.75	0.42	0.15	0.11
5% level significant correlation	0.34	0.17	0.28	0.35

Table 6.2: Variance explained by the first four modes for PCA performed on NOAA Extended Reconstructed SST anomalies and on SST anomalies derived from casts along Line-P. Correlations between the temporal coefficients found for each data sets and the 5% level significance correlation.

Figure 6.2: First four spatial modes for PCA performed on NOAA Extended Reconstructed SST anomalies (dashed lines) and on SST anomalies derived from casts along Line-P (solid line).

The four first spatial patterns are very similar, although noisier for the SST anomalies derived from Line-P casts. The first modes show a uniform variability for the whole domain. The main difference between the two patterns is at the coast, where the spatial resolution is finer for Line-P samples. The second modes both show a bipolar West-East variability. Other modes also show similar patterns for both data sets.

The Line-P derived SST anomalies are noisier, which is seen in the spreading of variance into higher modes (Table 6.2). Nevertheless, the main modes, the first two, are significantly correlated at the 5% level. This test was derived from the Student's *t* distribution, and the effective sample sizes were calculated using (Emery and Thomson, 1997, p. 260)

$$N_{eff} = \frac{N}{\sum_{l=-L}^L [\rho_{xx}(l)\rho_{yy}(l) + \rho_{xy}(l)\rho_{yx}(l)]}$$

where *x* and *y* refers to the temporal coefficients obtained from the two data sets, *N* the number of time points, $\rho_{xy}(l)$ the correlation between the *x* and *y* time series with a lag *l*. We chose $L = N/3$.

This comparison shows good agreements between the two data sets, even if the Line-P data are noisiest

at the surface. The Approximated Principal Component Analysis performed on the Line-P casts data from surface to 500 m is expected to give significant modes, despite the noise.

PCA results

PC#	1	2	3	4	5	6	7	8	9	10
Variance explained	25.33%	9.93%	6.74%	4.22%	3.94%	3.36%	2.73%	2.52%	2.46%	2.06%
relative decrease of variance		0.61	0.32	0.37	0.07	0.15	0.19	0.08	0.02	0.16

Table 6.3: Variances explained by the first 10 modes of the PCA performed on temperature anomalies along Line-P and the relative decreases in the variance of the mode i relative to the previous one, i.e. $\{[\text{Variance mode } i-1] - [\text{Variance mode } i] \} / [\text{Variance mode } i-1]$.

Figure 6.3: First three PCA modes for temperature anomalies along Line-P.

Appendix 3: t test

The 5% level test used to determine the significance of a correlation between two time series consists of a t test (Von Storch and Zwiers, 1999, sec. 6.6.1.). The correlation ρ_l for which 95% of random time series give inferior values from a t -distribution is the threshold value, determine using

$$\rho_l = \frac{t^2}{N - 2 + t^2}$$

where $t=2.04$ from t -distribution tables, and N is the sample size if all values are independent. In the case of our data, time series are always autocorrelated to some extent. We approximate the effective sample size by

$$N_{eff} = \frac{N}{\sum_{l=-L}^L [\rho_{xx}(l)\rho_{yy}(l) + \rho_{xy}(l)\rho_{yx}(l)]}$$

where x and y refer to the two time series for which the correlation is calculated, l the lag considered (Emery and Thomson, 1997).

Appendix 4: First SLPA modes

1st PCA mode for SLP ano.
Variance explained: 33.39%

Figure 6.4a : First three PCA modes for broad-scale SLP anomalies; 1st mode.

Figure 6.4b : First three PCA modes for broad-scale SLP anomalies; 2nd mode.

Figure 6.4c : First three PCA modes for broad-scale SLP anomalies; 3rd mode.