NATURAL HAZARDS RESEARCH PLATFORM

Contest 2015

Title: High Water Red-Alert Calendar including Monthly Mean Sea Level Anomaly

Leader: Emily Lane/Rob Bell
Organisation: NIWA
Total funding (GST ex): $150,000

Title: High Water Red-Alert Calendar including Monthly Mean Sea Level Anomaly

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Affiliation: NIWA

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Key message for media:

Coastal flooding or erosion are more likely to occur on days with especially high tides. The background mean sea level varies slowly and can be up to 20 cm higher or lower depending on climate conditions. We can forecast this up to 6 months in advance. By combining this with tide predictions we can highlight days that are prone to coastal flooding. If a storm or large waves also occur on these days, the chance of flooding is especially high.

Abstract:

Coastal inundation and erosion cause millions of dollars of damage in New Zealand. Because of New Zealand's location in the mid latitudes, these are usually a result of a combination of tides, mean sea level anomaly, storm surge and waves. While tides are astronomically-driven and can be predicted many years in advance, the mean sea level anomaly is driven by the climate. This gives us the possibility of forecasting it up to a few months into the future. We develop a forecasting system to predict mean sea level anomaly up to 6 months into the future and use this to create a high-water red-alert calendar which forewarns emergency managers of days at higher risk of coastal inundation.

Keywords:

Coastal inundation, coastal erosion, mean sea level anomaly, high tide, king tide

Introduction / Background:

Coastal inundation and erosion cause millions of dollars of damage in New Zealand. For example, on 23 January 2011 Auckland experienced coastal inundation (~90 year ARI (Average Recurrence Interval) compounded by sea level rise) which resulted in $6.9 million worth of insurance claims (Stephens, Goring et al. 2014), not including additional costs such as traffic disruption, clean-up and lost work time. More recently, in April 2014, ex-tropical Cyclone Ita caused coastal storm inundation in Auckland and Tasman District (Stephens, Goring et al. 2014). With ongoing sea-level rise these events will occur much more often, e.g. in Auckland a 23-January-2011 type event will occur on average 3 times per year with only a 0.45 m sea level rise, with consequential escalation in damage costs and disruption (Parliamentary Commissioner for the Environment 2014).

New Zealand's location in the mid latitudes and our medium to large tidal range means that coastal-storm inundation results from a combination of tides, mean sea-level anomaly (MSLA), storm surge and waves. Previous research has shown that, because the tide is the largest component of sea-level variability, the highest storm-tides in New Zealand usually occur at times of higher-than-normal high tides, often compounded by high background MSLA (Bell, R.G. and Goring 1996; Gillibrand, Lane et al. 2011). By providing extra warning of these days we create a more resilient society that is better able to cope with these events.

Dates of higher-than-normal high tides are already forecast in NIWA's red-alert tide calendar (NIWA 2017). The red-alert tide calendar is already well known and used as a 'heads-up' by Civil Defence and emergency managers within New Zealand Councils whose regions contain significant coastal development and infrastructure. On red-alert tide days,

coastal hazard managers are advised to keep a close watch on the weather, waves and forecasts for lower barometric pressure and adverse winds as even a minor storm could lead to inundation of low-lying areas, especially if accompanied by swell. The red-alert tide calendar also has a following amongst the general populace. The popular Auckland king tide website (Recreation Solutions 2017) links to the NIWA red-alert tide calendar for king tide alerts throughout New Zealand.

Recent research in New Zealand and the Pacific has shown that the inclusion of MSLA considerably enhances the prediction of high-water alert levels, with a more realistic connection to what actually occurs (Stephens, Bell et al. 2014). While the original calendar was based on tides alone, our improved calendar also incorporates predicted MSLA to more accurately identify high and low risk times. Additionally, whereas the existing high-tide calendar is produced for a single calendar-year on an ad-hoc basis, the new calendar is produced on a monthly basis and forecasts 12-months in advance. MSLA are forecast using a combination of the previous sea level record, satellite altimetry data, climate data and a MSLA forecast.

Impact Statement 1: Operational forecasting of Sea Level Anomaly and incorporation within high-water red-alert calendar

Research Aim 1.1: Sea-level data analysis

❖ **1.1 Research Aim**

Title: Sea-level data analysis

Budget: $50,000

Research Aim achieved? Yes

- **list of outputs**
  - **Sea level data for New Zealand stations collected, processed, separated into 12 month running-average, mean seasonal cycle and residual MSLA.**
  - **Climate data collected and processed.**
  - **Climate indices – calculated relative to 1980-2010 climatology.**
  - **Climate Atlas created highlighting correlations between sea level and climate data**
- **list of end-users**
  - **New Zealand researchers**
  - **Local and Regional councils**
  - **Civil Defence and Emergency Managers**

Sea level gauge data was collected for locations around New Zealand. Appendix 1 gives the sea level stations where data was collected and the time periods each station covers. The records vary considerably in time-span covered and quality. Short time records and large gaps for some of the gauges make the process of determining relationships with climate or with other gauge locations difficult. The data was processed as outline in Appendix 1 and decomposed into 12-month running average, mean seasonal cycle and MSLA residual. These three components are what we use in the MSLA forecasting.

With a view to extending the forecast spatially we compared the MSLA residuals around New Zealand. This was hampered by the patchiness of the data meaning that there was no single time when we had good forecasts throughout New Zealand. Appendix 2 give more details of the analysis. We found distinct regions where the MSLA residual acted coherently, in that the timing of high or low MSLA was clearly related to other sites. The strongest of these regions were the northern part of the east coast of the North Island and the southern part of the east coast of the South Island. The central New Zealand region also showed some coherence but it was not as strong and the other two regions. There was not enough data on the west coast of New Zealand to clearly identify coherent regions. At times the MSLA residual is coherent over the whole of New Zealand, while at other times the separate regions have different responses.

In addition to sea level data, climate data (Temperature, air pressure and wind) was collected and climate anomalies and climate indices (SAM, NINO3.4, SOI) were calculated (See Appendix C for details). Atlases were created comparing the MSLA residual with different climate data and indices both for linear and non-linear, direct and lagged response. This analysis showed that the main large-scale climate mode influencing variability in the MSLA residuals around NZ is the El Nino – Southern Oscillation (ENSO): warmer than normal Sea Surface Temperatures (SSTs) in the central and Equatorial Pacific Ocean (*i.e.,* El Niño) is generally associated with below normal MSLA for all stations, while La Niña (cooler than normal SSTs in the central and equatorial Pacific) are related to above normal MSLA. However, significant variability in the strength of this relationship with the individual MSLA stations exists, and the correlations are generally highly dependent upon the seasonal cycle, with maximum correlations shown during the summer. Lead-lag and seasonally dependent relationships between the individual stations MSLA and indices encapsulating ENSO variability, such as the NINO3.4 SST index, or the Southern Oscillation Index, indicate that some degree of predictability for MSLA arising from climate modes exist, with strong correlations existing with a 1- to 3-months' lead time especially during the summer months.

When building the statistical – dynamic model (see below), these relationships have motivated the inclusion of the NINO3.4 index as an independent variable (predictor), as well as the consideration of the month of the forecast via the inclusion of an indicator variable.

Research Aim 1.2: Sea-level Anomaly prediction

- **1.2 Research Aim**

Title: Sea-level anomaly prediction
Budget: $50,000
Research Aim achieved? Yes

- **list of outputs**
    - **monthly prediction of MSLA out to six months in advance**
- **list of end-users**
    - **New Zealand researchers**

We forecast MSLA for Marsden Point, Auckland, Moturiki, Wellington, Lyttelton and Dunedin, being the six stations with the longest (>20 years) good quality sea level records. As discussed in Research Aim 1.1 above, we decompose the MSLA into ASLA, mean seasonal cycle and MSLA residual, predict these separately and then reconstruct them. We do this because, while the CFSv2 forecasts are a reasonable predictor of short term MSLA behaviour, they do not represent long-term variations well.

The ASLA is either calculated directly from observations or (for stations for which we do not have real-time observation) estimated from satellite altimetry from the previous 12 months. The mean seasonal cycle is assumed to be stationary and is calculated from historical observations. The monthly MSLA residuals are forecast 6 months into the future, using a statistic-dynamic model to combine results from dynamic model forecasts of regional Sea Surface Height (SSH) and the observed state of the El Nino Southern Oscillation. The details of the data used and where it is sourced from are given in Appendix D and the methodologies for the prediction of the MSLA residual and the ASLA from satellite altimetry are given below.

Statistico-dynamic model relating MSLA forecasts and NINO3.4 to MSLA residual

We forecast the MSLA residual with a statistic-dynamic model using the MSLA residual calculated from NOAA's CFSv2 dynamic model (Saha, Moorthi et al. 2013), the NINO3.4 climate index and the forecast month as predictors.

First, for each station, we first build a statistical model relating the regional-scale information contained in the monthly MSLA forecasts from CFSv2 to the observed, coastal time-series of monthly MSLA residual at that station. This step is necessary because the CFSv2 forecasts are not provided / not accurate at the coast. This location specific forecast MSLA index time-series is created by averaging the forecast MSLA for all grid-points showing a large correlation with the observed, station MSLA (see Figure 1).

The past 3 months averaged SSTs anomalies in the NINO3.4 region are also a predictor, as well as the month of the forecast, coded as a categorical variable. The linear model can thus be written:

$$MSLA(x) = \alpha(i,x) \times CFSv2(x) + \beta(i,x) \times NINO3.4 + \gamma(i,x)$$

Where *i* = 1, 2, …,12 according to the month of forecast and *x* represents the station being solved for. Values for $\alpha(i,x)$, $\beta(i,x)$ and $\gamma(i,x)$ are fitted using the historical data. Figure 2 shows predictions for Auckland from this model. Predictions of MSLA residual for the next 6 months are made as this was the prediction window that was seen to have reasonable skill. Further out than this the forecasts are less and less accurate.

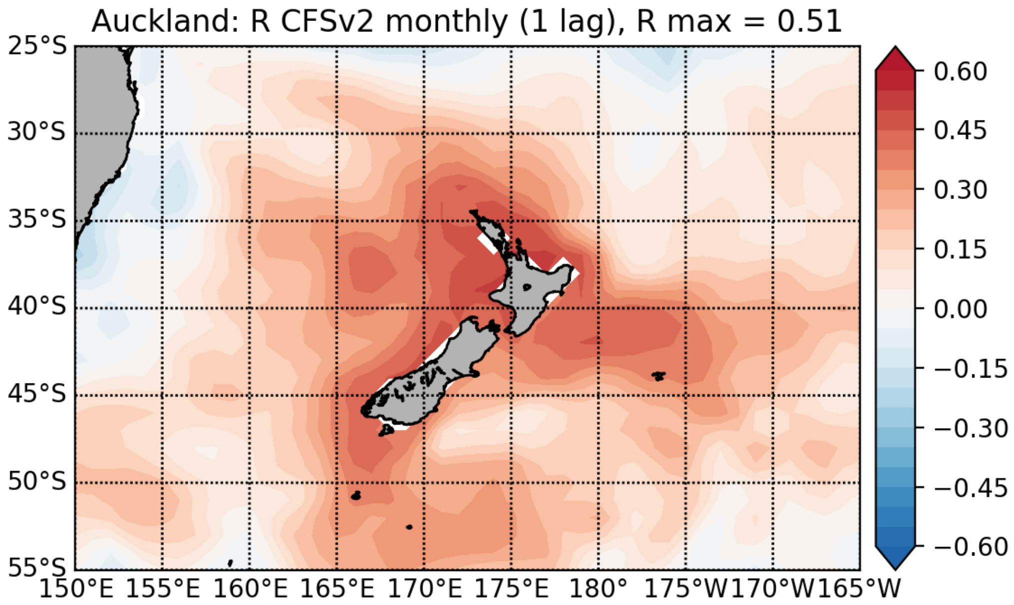


Figure 1*: correlation between observed monthly MSLA anomalies in Auckland and the one month lead time CFSv2 forecast MSLA. For both time-series and predicted fields, a running 12-month average has been removed prior. For the observed time-series of MSLA in Auckland, this running average is made lead-time dependent, so that e.g. the forecasts for month +1, +2 …, +6 is always expressed as an anomaly WRT the last available 12 months.*

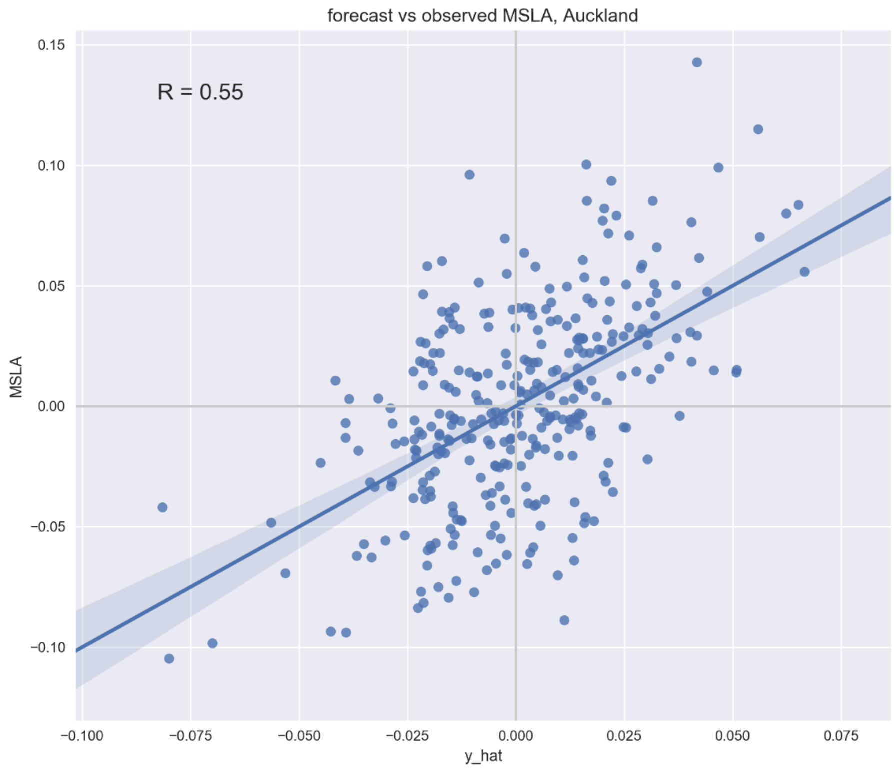
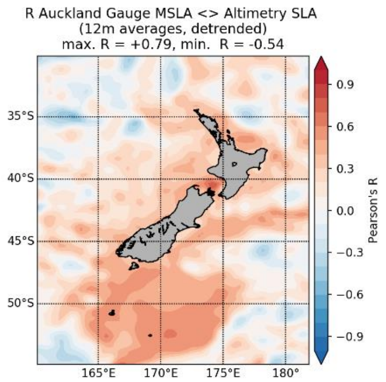


Figure 2: *observed (y-axis) vs predicted (x-axis) monthly mean MSLA in Auckland using the linear model* $MSLA(x) = \alpha(i,x) \times CFSv2(x) + \beta(i,x) \times NINO3.4 + \gamma(i,x)$.

Satellite estimates of the past 12 months MSLA

Where the observations are available in near real time the ASLA will be calculated directly from them. This is not always the case and so the ASLA can also be *estimated by satellite remote sensing*. The Figure 3(LHS) presents the correlation field between the 12 months running averages of monthly MSLA in Auckland and the 12 months running average of the satellite altimetry estimates, over the common period 1994 – 2016. For all stations, the maximum correlations exceed 0.6, indicating that the satellite altimetry signal can to some extent be used to estimate the past 12 months coastal MSLA. The Figure 3(RHS) presents the bathymetry around NZ, and shows that large correlations between the Auckland observed MSLA and the satellite estimates correspond to relatively shallow-water regions (< 1500 m. deep), the same general pattern is observed for all stations.

Following the MSLA residual methodology the location station ASLA is estimated by first creating a local index as the average of the top 10% correlated points for the ASLA for each station. A simple linear regression is fitted for the ASLA at the station using the historical ASLA observations.



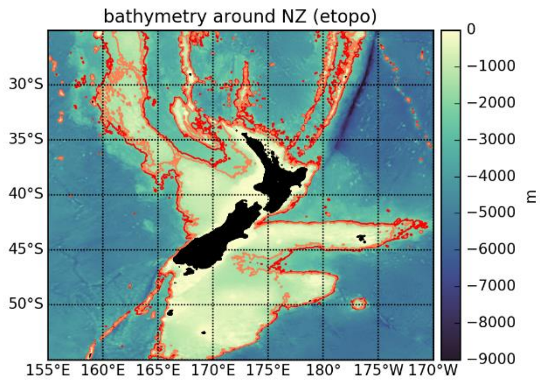


Figure 3*: (LHS) correlations between the 12 months running averages of monthly MSLA in Auckland and the 12 months running averages of Satellite-derived MSLA. (RHS) bathymetry around New Zealand.*

The forecast MSLA for the next 6 months at each location is made up by combining the ASLA for that stations with the mean seasonal cycle value and MSLA residual predicted for the given month.

Research Aim 1.3: High-water-alert calendar

❖ **1.3 Research Aim**
Title: High-water-alert calendar
Budget: $10,000
Research Aim achieved? Yes
Please include:

- **list of outputs**

- High-water red-alert calendars for 6 locations around New Zealand

- **list of end-users**
  - **Local and regional councils**
  - **Civil defence and emergency managers**
  - **General public**
  - **New Zealand researchers**

We have developed a template high-water calendar that allows us to combine predictions of MSLA calculated in the previous research aim 1.2 with high-tide predictions to produce more accurate high-water red-alert calendars specific to each location. Additionally, for each location, we have calculated values of the top 1%, 5% and 10% combined high-tide plus MSLA. In the calendar, we highlight days as red, orange or burnt yellow if the maximum forecast high tide plus MSLA for that day exceeds the 1%, 5% or 10% threshold respectively. This information is provided in both a full year calendar for quick reference (Figure 4) but also a more detailed month-by-month calendar where heights and times of the high tides and a visual representation of the tide plus MSLA are also shown (Figure 5). The more in-depth view also shows the height of a 1% annual exceedance probability storm-tide, as well as lowest and highest astronomical tide for that location.

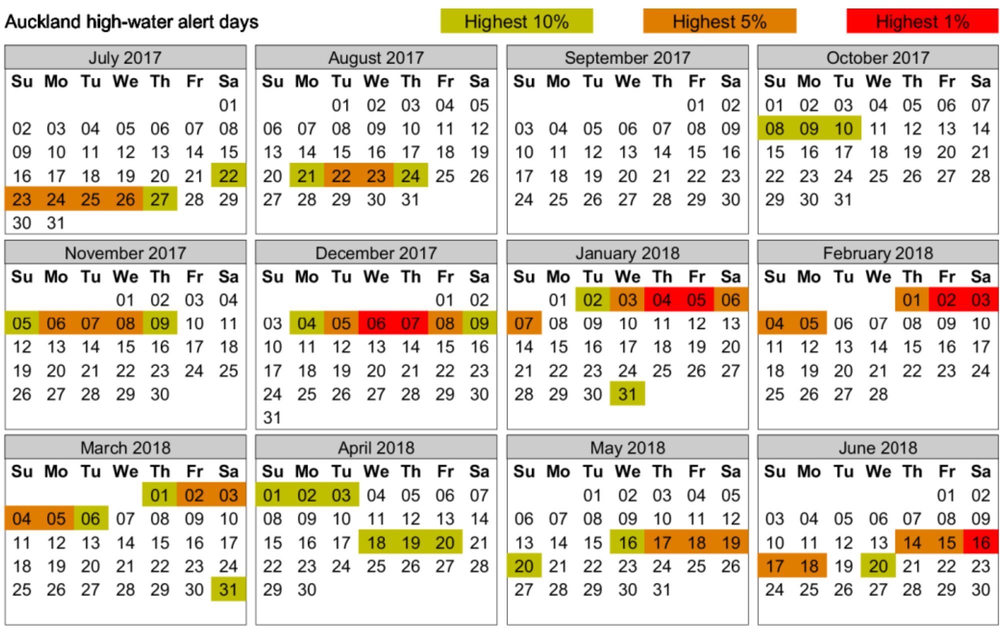


***Figure 4**. A quick reference full year Red Alert Calendar for high tide plus MSLA as produced for Auckland in the month of July.*

Auckland, July 2017: predicted tide + mean sea level

Sun	Mon	Tue	Wed	Thu	Fri	Sat
						Sat 01 Jul
						00:45 1.34
						06:55 -1.17
						13:15 1.17
						19:10 -1.07
Sun 02 Jul	**Mon 03 Jul**	**Tue 04 Jul**	**Wed 05 Jul**	**Thu 06 Jul**	**Fri 07 Jul**	**Sat 08 Jul**
01:40 1.22	02:30 1.11	03:25 1.04	04:15 1	05:10 0.98	05:55 0.99	00:25 -0.93
07:50 -1.09	08:40 -1.03	09:35 -0.99	10:25 -0.97	11:20 -0.98	12:05 -1.01	06:40 1.02
14:10 1.07	15:05 1	16:05 0.99	17:00 1.01	17:50 1.06	18:35 1.12	12:50 -1.06
20:10 -0.96	21:05 -0.9	22:00 -0.87	22:50 -0.87	23:40 -0.89		19:15 1.17
Sun 09 Jul	**Mon 10 Jul**	**Tue 11 Jul**	**Wed 12 Jul**	**Thu 13 Jul**	**Fri 14 Jul**	**Sat 15 Jul**
01:10 -0.98	01:50 -1.03	02:30 -1.08	03:10 -1.12	03:50 -1.15	04:35 -1.17	05:20 -1.17
07:25 1.05	08:05 1.09	08:45 1.12	09:25 1.15	10:05 1.16	10:50 1.16	11:35 1.15
13:30 -1.11	14:05 -1.17	14:45 -1.21	15:20 -1.22	16:00 -1.22	16:45 -1.19	17:30 -1.14
19:55 1.21	20:35 1.25	21:10 1.27	21:55 1.28	22:35 1.28	23:20 1.27	
Sun 16 Jul	**Mon 17 Jul**	**Tue 18 Jul**	**Wed 19 Jul**	**Thu 20 Jul**	**Fri 21 Jul**	**Sat 22 Jul**
00:05 1.25	00:50 1.24	01:45 1.23	02:40 1.23	03:40 1.25	04:45 1.3	05:45 1.38
06:05 -1.17	07:00 -1.18	07:50 -1.2	08:50 -1.23	09:50 -1.29	10:50 -1.37	11:50 -1.46
12:20 1.13	13:15 1.12	14:10 1.13	15:15 1.17	16:20 1.26	17:20 1.39	18:20 1.52
18:20 -1.09	19:15 -1.05	20:20 -1.05	21:20 -1.08	22:20 -1.15	23:20 -1.23	
Sun 23 Jul	**Mon 24 Jul**	**Tue 25 Jul**	**Wed 26 Jul**	**Thu 27 Jul**	**Fri 28 Jul**	**Sat 29 Jul**
00:20 -1.33	01:20 -1.41	02:10 -1.47	03:05 -1.49	03:50 -1.45	04:40 -1.38	05:30 -1.28
06:45 1.45	07:40 1.52	08:35 1.55	09:25 1.54	10:15 1.49	11:05 1.41	11:55 1.3
12:45 -1.55	13:40 -1.62	14:30 -1.64	15:20 -1.6	16:05 -1.49	16:55 -1.35	17:45 -1.19
19:15 1.63	20:10 1.68	21:00 1.69	21:50 1.65	22:40 1.56	23:30 1.45	
Sun 30 Jul	**Mon 31 Jul**					
00:15 1.32	01:05 1.19					
06:20 -1.17	07:10 -1.06					
12:40 1.17	13:35 1.06					
18:35 -1.04	19:30 -0.92					

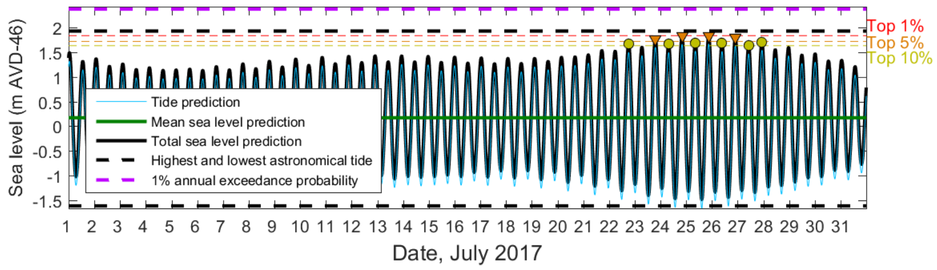


Figure 5: *Detailed monthly view of July 2017 for the red alert calendar. The times and heights of high and low tides are given, colour-coded to show the top 1%, 5% and 10%. A forecast time-series for tide and MSL for that month.is also shown marked with critical levels.*

Research Aim 1.4 Operational forecasting

❖ 1.4 Research Aim

Title: Operational forecasting

Budget: $10,000

Research Aim achieved? Yes

- **list of outputs**
  - **Operational, online forecasts**
- **list of end-users**
  - **Local and regional councils**
  - **Civil defence and emergency managers**
  - **General public**
  - **New Zealand researchers**

We provide operational high-water-alert forecasts, including predictions of MSLA up to six months in advance, and updated monthly at locations around New Zealand, based on the outputs from research aims 1.1–1.3.

At the beginning of each month, data from CFSv2, the sea level network and the satellite altimetry network are downloaded and processed using python scripts to produce forecasts of MSLA for the next six months as outlined in the methodology of research aim 1.2. Where the sea level network data is available, this is used for the annual running average of the sea level anomaly. If this data is not available near real time or in situations where it may be missing for any reason, we have the fall-back of using a statistical model of the annual MSLA calculated from nearby satellite data outlined in Research Aim 1.2. This ensures continuity of results even if the sea level data is late or missing. Using the process from Research Aim 1.3 this is converted into calendars for each location which are then posted online. Alert days are provided for the next 12 months, of which the first six months include the forecast MSLA. Beyond 6 months the forecast skill is not high so only the mean seasonal cycle of the MSLA is included. These forecasts are available online at https://www.niwa.co.nz/natural-hazards/physical-hazards-affecting-coastal-margins-and-the-continental-shelf/High-tide-red-alert-calendar.

Research Aim 1.5 Communicating and transferring outputs

❖ **1.5 Research Aim**
Title: Communicating and transferring outputs
Budget: $30,000
Research Aim achieved? Partially – manuscript still to finish
Please include

- **list of outputs**
  - **Oral presentations at NZCS conference, November 2016, and NHRP workshop, August 2016.**
- **list of end-users**
  - **Local and regional councils**
  - **Civil defence and emergency managers**
  - **General public**
  - **New Zealand researchers**

Our research has been presented at the New Zealand Coastal Society conference in Dunedin in November 2016:

Lane, E.M., Fauchereau, N., Stephens, S. Robinson, B., Spatial and temporal variability in the Monthly Mean Sea Level Anomaly around New Zealand. Oral presentation at New Zealand Coastal Society Conference, Dunedin New Zealand, November 2016. It was also presented at the NHRP workshop held at GNS in Avalon, Lower Hutt in August 2016.

This conference and workshop reach other researchers and scientists; engineers and consultants and people in local and national government with an interest in the coastal area. These are all people potential end-users of our work.

Progress is well underway to produce a manuscript reporting the methodology behind the MSLA forecasting. This was delayed because issues obtaining regular sea level observations meant that we had to develop a statistical model to determine the 12-month running average sea level from satellite data in case the real-time gauge observations were not available. This was extra work that needed to be addressed before the MSLA forecast could become operational. This manuscript will be finished and submitted early in the 2017/18 financial year. A second manuscript reporting on the regional variation in the sea level anomaly is planned for later in 2017/18.

The calendar is available online at https://www.niwa.co.nz/natural-hazards/physical-hazards-affecting-coastal-margins-and-the-continental-shelf/High-tide-red-alert-calendar, and will be updated monthly as forecasts are made. The website link has been emailed directly to coastal hazard managers at Auckland, Bay of Plenty, Waikato, Greater Wellington, Christchurch and Otago regional councils.

Conclusions & Recommendations:

We have developed a statistical-dynamic forecasting system that predicts MSLA up to 6 months in advance. We use these predictions to improve the accuracy of the red-alert high-water calendar. Additionally, whereas the existing high-tide calendar is produced for a single calendar-year on an ad-hoc basis, the new calendar is produced monthly and forecasts 12-months in advance. This calendar alerts local and regional councils, civil defence and emergency managers of dates with very high high-waters, when we are more likely to suffer inundation or coastal erosion if there are storms or high waves during these times.

We also investigated the make-up of the MSLA, its annual, seasonal and residual components and their drivers. We analysed the spatial variability of the MSLA residual and identified regions where it tends to act coherently and boundaries between these. Relationships between climate drivers and MSLA residuals were quantified. This research gives more insight into drivers of MSLA in New Zealand in different regions and at different timescale and provides a platform for further research.

This work is ongoing with MSLA forecasts being produced monthly, verification should also be ongoing to compare forecast and observed levels over longer time periods. It would be worthwhile to extend the MSLA forecasting to other regions around New Zealand, first to other locations with sea level gauges as we get longer records where we are able to properly train the model (possibly leveraging of nearby long-term sea level gauges) and then further to regions without sea level gauges using our research on spatial extents of MSLA.

This would be particularly difficult on the west coast due to the paucity of sea level gauges. Calendars could also be further improved by the addition of carefree days – days when the forecast high-tide plus MSLA as predicted to be more than a given amount below a 1:100 AEP event. On these days coastal inundation and erosion are much less likely. Ideally the MSLA should be included in all sea-level forecasting so that heights are relative to a known datum.

Acknowledgements:

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Appendices:

Appendix A: Sea level data

Data collection

We collected sea level data from a range of sources including NIWA data, ports and GeoNet (although the latter are pressure sensors and thus prone to drift. This makes them less useful for studies of long term fluctuations). Table A.1 gives a list of all the stations collected and figure A.1 shows the spatial and temporal distributions of the records. It can readily be seen that there are not many long-term records and even those there are often have large gaps in the data. Coverage is especially sparse on the west coast of central and southern New Zealand.

Table 0-1 List of stations where sea level records were collected arranged from North to South. The location, length of record, whether it is still operational and any significant gaps in record are also indicated.

Station	*Longitude*	*Latitude*	*Years of data*	*Operational*	*Gaps*
North Cape	173.05	-34.4167	6.7	Yes	
Whangaroa Harbour	173.7437	-35.0496	5.8		
Opua	174.1211	-35.3122	23.7		
Marsden Pt	174.5	-35.842	26.2	Yes	
Mokohinau Island	175.1109	-35.9072	6.2		
Dargaville	173.8722	-35.9413	34.6	Yes	Yes
Korotiti Bay, GBI	175.4833	-36.1833	5.1	Yes	
Pouto Point	174.1816	-36.3626	13.5	Yes	Yes
Whitianga	175.709	-36.833	16.1	Yes	
Auckland	174.7682	-36.8412	110.8	Yes	Yes
Anawhata	174.4514	-36.9285	13.3		
Manukau	174.5167	-37.05	5.1	Yes	
Tararu	175.521	-37.128	25.2	Yes	
Lottin Point	178.1667	-37.55	6.9	Yes	
Moturiki	176.193	-37.633	44.2	Yes	
Tauranga	176.1833	-37.65	7.1	Yes	
Raglan Pier	174.88	-37.7944	7.8	Yes	Yes
Manu Bay	174.8142	-37.8221	3		
Kawhia	174.8232	-38.0659	7	Yes	
Gisborne	178.0333	-38.667	5.7	Yes	
Port of Gisborne	178.0229	-38.6755	9		Yes
Port Taranaki	174.033	-39.055	32.1	Yes	
Napier	176.9167	-39.4833	7.9	Yes	
Tarakohe	172.898	-40.823	10	Yes	
Kapiti Island	174.938	-40.842	15		
Castlepoint	176.2167	-40.9167	5.9	Yes	
Little Kaiteriteri	173.027	-41.048	10	Yes	
Porirua Harbour	174.866	-41.1	3		
Nelson	173.2731	-41.2616	31.2	Yes	Yes
Wellington	174.7798	-41.2845	70	Yes	Yes
Charleston	171.433	-41.908	14.9		Yes
Kaikoura	173.703	-42.415	12.6		
Sumner Head	172.773	-43.57	21.2	Yes	Yes
Lyttelton	172.7222	-43.6058	110		Yes
Kaingaroa	183.733	-43.7315	10.7		
Akaroa	172.96458	-43.8001	0.4		
Jackson Bay	168.616	-43.957	5.2		Yes

Station	*Longitude*	*Latitude*	*Years of data*	*Operational*	*Gaps*
Chatham Islands	183.6333	-44.0333	7.7	Yes	Yes
Timaru	171.254	-44.392	13.7	Yes	
Port Chalmers	170.6333	-45.8167	5.5	Yes	
Dunedin	170.51	-45.879	114		Yes
Green Island	170.383	-45.956	12.7	Yes	
Puysegur	166.5833	-46.0833	5.7	Yes	
Dog Island	168.412	-46.652	18.5	Yes	

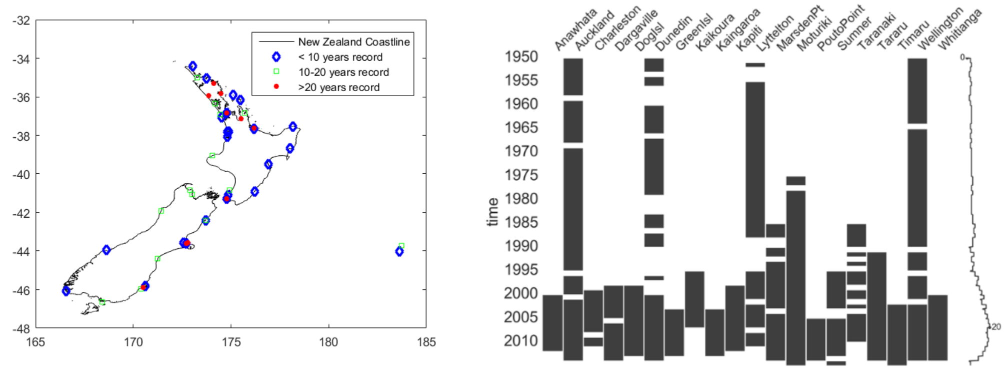


Figure A.1 *LHS: Spatial coverage of sea level gauges coded by length of record. RHS: Sea level gauge time coverage.*

Processing of the sea level records.

Records with more than 5 years of data were quality-checked to remove erroneous data spikes, and correct for datum shifts and drifts, and timing errors. The sea-level record was decomposed into predicted tide and non-tidal residual. The non-tidal residual was detrended, and the MSLA was extracted from the non-tidal residual by calculating the average non-tidal residual for each calendar month, following for example, (Stephens, Bell et al. 2014). For each gauge, the MSLA was further decomposed into a 12-month running average sea level anomaly (ASLA), the mean seasonal cycle and a de-seasoned MSLA residual.

The mean seasonal cycle was calculated by first removing the ASLA and then averaging over each month. It was only calculated for sites with a record length of at least 10 years of gap free data as it can't be reliably computed for sites with short records.

Figure A.2 shows the component parts of the MSLA. ASLA can be up to ±10 cm, is relatively consistent throughout New Zealand and correlates well with the Southern Oscillation index (Goring and Bell 1999; Hannah and Bell 2012). The amplitude of the mean seasonal cycle varies from site to site, but is strongest in to the north of New Zealand where it can be up to ±8 cm but is generally around ±5 cm. The mean seasonal cycle is strongly correlated with the temperature and but not with inverse barometer (i.e. the effect of barometric air pressure). This suggests that the heating effect of the temperature is enough to overcome the inverse barometer effect which is working in the opposite sense (Bell, R. G. and Goring 1998).

We use these components of the MSLA in our forecasting as outlined in research aim 1.2.

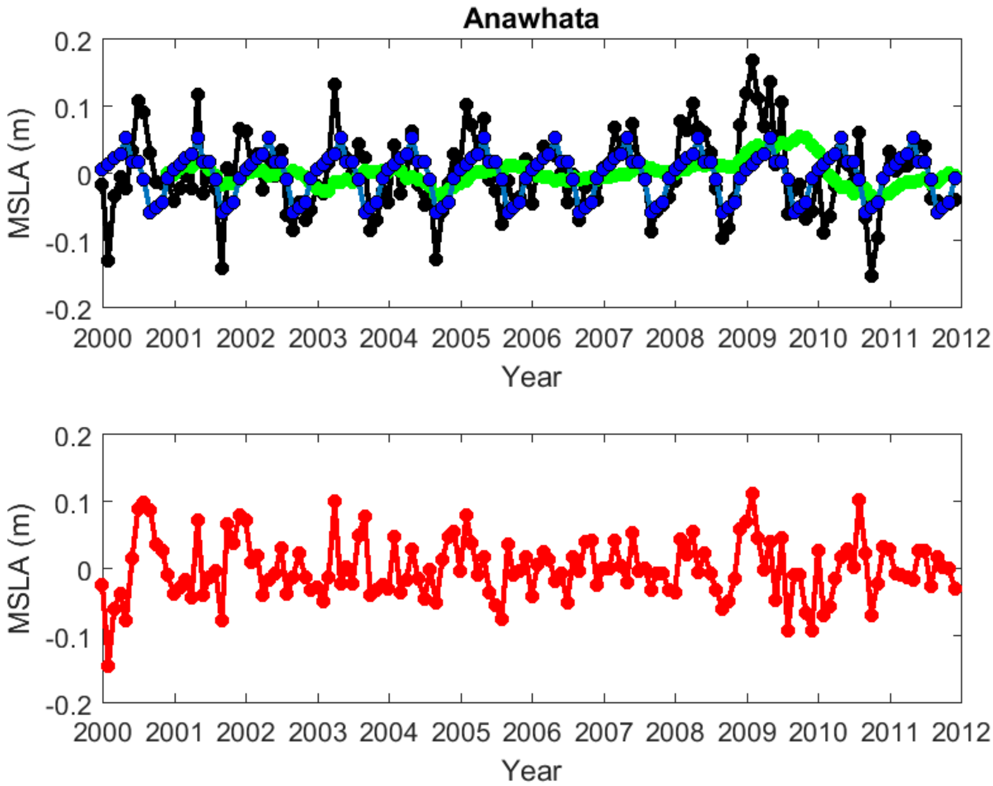
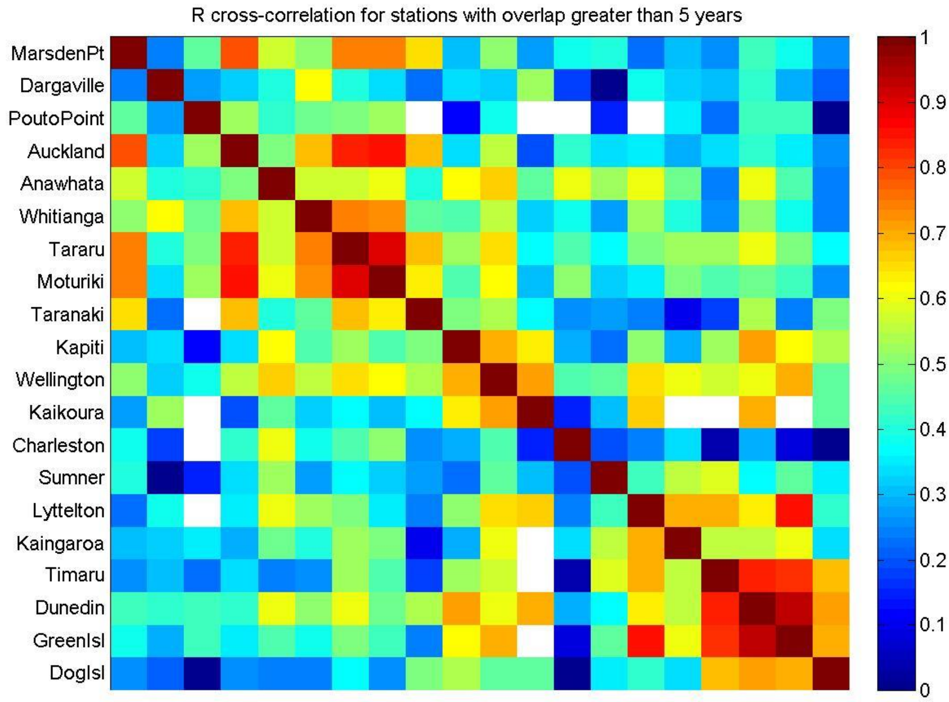


Figure A.2: *Example of MSLA decomposition for Anawhata. Top: monthly MSLA (black), 12 month running average (green) and mean seasonal cycle (blue). Bottom: residual MSLA.*

Appendix B: Spatial variability in MSLA

The spatial coherence of the MSLA was investigated by analysing the correlation between different sea level stations. This analysis was hampered by the paucity of over lapping records and we were unable to find any one appreciable length of time when most the records overlapped. To maximise the information obtained from the data for each pair-wise comparison of data we consider the entire period that those two records overlap. Those stations with overlaps of greater than 5 years were compared. Figure B.1 shows matrices of the correlations of the stations – red indicates strong correlation. Results show that there are clearly regions around New Zealand where MSLA seems to act in concert. Most notable among these are the north-east of the North Island and the south-east of the South Island. There is also a central block covering Kapiti, Wellington and Kaikoura although this relationship is not as strong. West coast stations are sparse and do not correlate very well with each other. Interestingly there are some stations that seem to connect regions, e.g., Lyttelton correlates well with both Kaingaroa (Chatham Islands) and Timaru although those two stations do not correlate well with each other. This suggests perhaps different regimes when different regions act together.



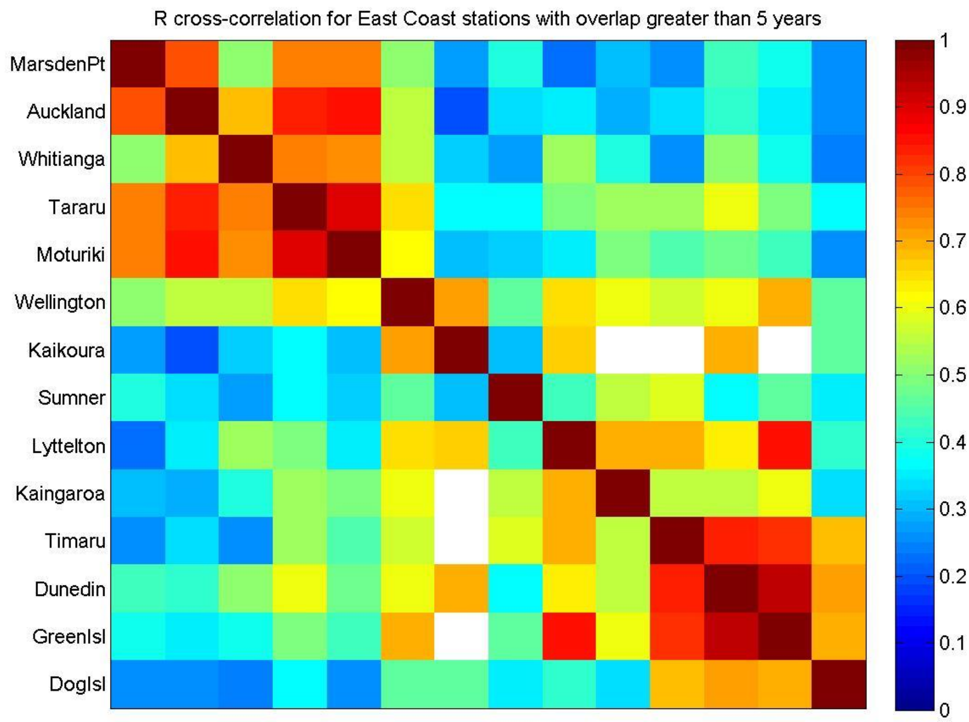


Figure B.1*. Correlations between stations with 5 or more years overlapping data (blank squares indicate lack of overlapping data). Stations are ordered from N to S, the top matrix contains all stations, the matrix contains only east coast stations.*

To investigate the timing of coherent sea level behaviour, twelve-month running correlations were calculated between the five longer gauge datasets (Auckland, Moturiki,

Wellington, Lyttelton and Dunedin) and the shorter gauge stations as shown in Figure B.2. This shows very interesting behaviour with different regions acting coherently at different times. Between 2000 and 2002 most stations were coherent and, to a lesser extent 2008-2010. At other times the North and South Island stations have responded more independently.

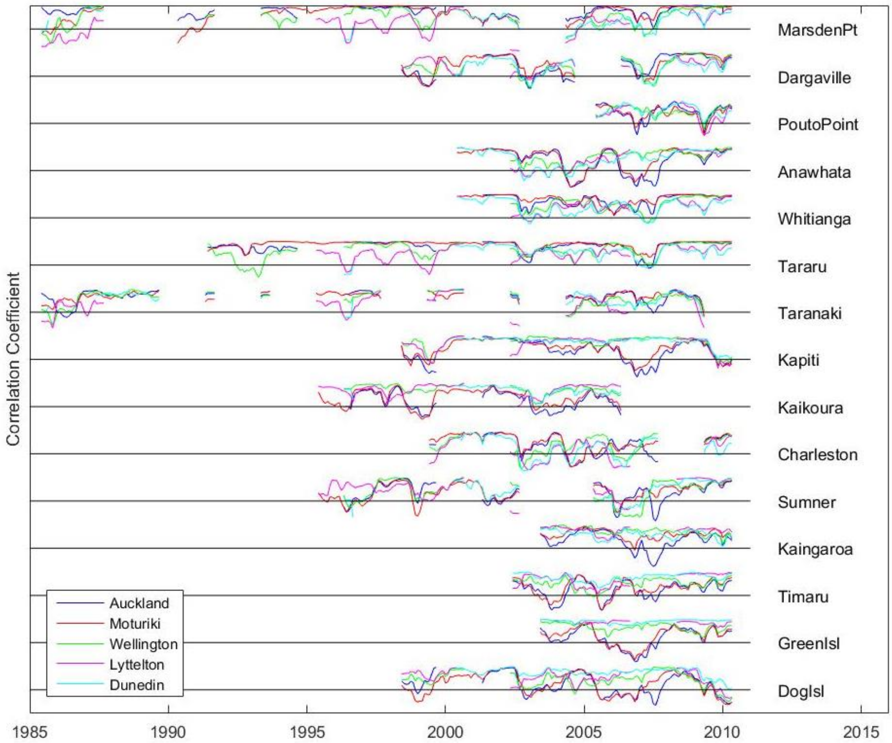


Figure B.2: Running 12-month correlations between longer and shorter term stations.

Appendix C: Climate Atlas.

Data collection

The following climate data was collected:

- monthly sea surface temperature (SST) from ERSST, 1948 – 2014 (Huang, Banzon et al. 2015).
- monthly geopotential (elevation above mean sea level where atmosphere reaches the given pressure e.g. 1000 hPa) at 1000, 850, 200 hPa from NCEP/NCAR (NCEP1) 1948 – 2014 (Kalnay, Kanamitsu et al. 1996).
- monthly meridional and zonal wind at 1000, 850, 200 hPa from NCEP/NCAR (NCEP1) 1948 – 2014 (Kalnay, Kanamitsu et al. 1996).

The following climate indices were also calculated with respect to a 1981 - 2010 climatology, i.e. anomalies were calculated with respect to mean values over that time-period.

- SOI (Southern Oscillation Index)
    - taken as the standardized difference between Mean Sea Level Pressure (MSLP) at Tahiti (French Polynesia) and Darwin (Northern Australia).
- NINO3.4
    - An index based on SST along the equator in the central Pacific that captures the current state of the El Niño – Southern Oscillation (ENSO) phenomenon (NOAA 2017).
- IPO (Inter-decadal Pacific Oscillation)

- calculated as the 2nd Empirical Orthogonal Function/ Principle component (EOF/PC) pair from filtered (> 11 years) SST anomalies).

- IOD (Indian Ocean Dipole)
  - calculated at the standardised difference between SST anomalies in the Western (10S to 0S / 50 to 70E)) and eastern (10S to 10N / 90 to 110E) tropical Indian Ocean.
- SPSD (South Pacific Subtropical Dipole)
  - calculated at the standardised difference between SST anomalies in the NW (50S to 35S / 170 to 190E)) and SE (57.5S to 45S / 220 to 240E) subtropical south Pacific.
- SAM (Southern Annular Mode)
  - extracted as the first PC on monthly anomalies of geopotential at 850 hPa.

Climate Atlas

We developed a climate atlas to identify regions which show similar MSLA trends and to develop correlations between sites. We used the four stations with the longest records, viz., Auckland, Wellington, Lyttelton and Dunedin see Figure A.1. Lagged linear and non-linear correlations were calculated between MSLA and sea surface temperature (SST), 1000 hPa geopotential height, zonal and meridional winds. Lagged correlations were also calculated between the MSLA and climate indices: NINO3.4, SAM, SPSD and IOD.

Linear Relationships between MSLA residual and large-scale climate fields

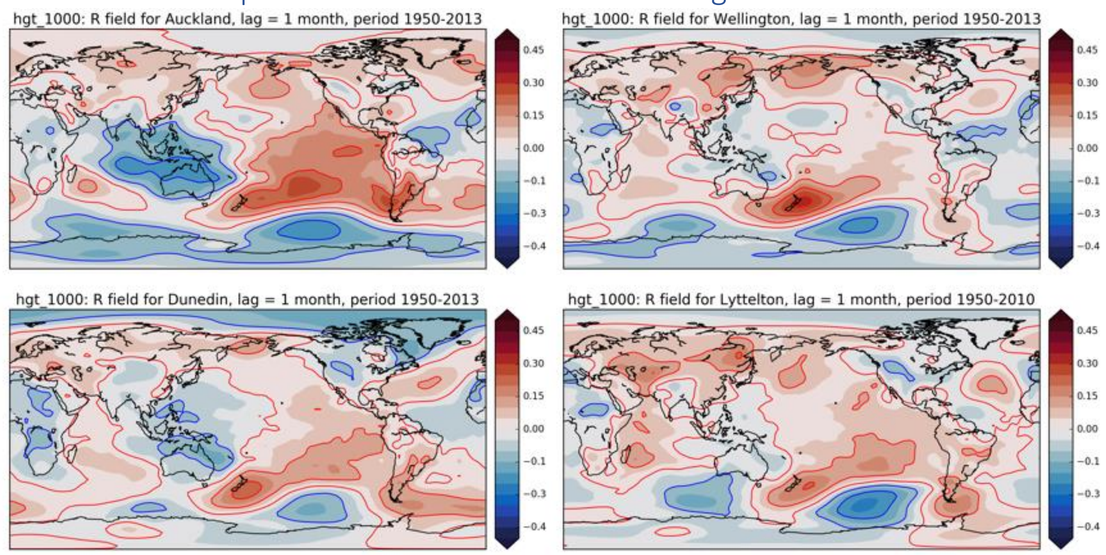


Figure C.1 *Correlation between the 4 long-term stations (Auckland, Wellington, Lyttelton, Dunedin clock-wise from top left) and 1000 hPa geopotential height for 1950–2013, based on a lag of 1 month.*

Figure C.1 shows linear correlation between MSLA residual and 1000 hPa geopotential height for the four stations. For Auckland, especially, the correlation field with geopotential anomalies reveals a very clear La Niña pattern, decreased atmospheric pressures over Indonesia and the Maritime continent, and increased atmospheric pressures over the southeast Pacific (i.e pattern typical of the Southern Oscillation [SO] component of the ENSO phenomenon). Elevated MSLA in Auckland is also associated with decreased atmospheric pressures at the high latitudes of the Southern Hemisphere, especially in the central Pacific.

For Wellington, Dunedin and Lyttelton, the large-scale ENSO pattern is less evident, but regional anomalies are relatively consistent, with increased atmospheric pressure over and east of NZ + decreased atmospheric pressure to the southeast (high latitude central Pacific) a common and relatively strong pattern.

Non-linear relationships between MSLA residual and large-scale climate fields

For each time-series of seasonal MSLA anomalies, samples corresponding to seasonal values above (below) the 90th (10th) percentile threshold are selected, see Figure C.2 below for an illustration using the time-series for Auckland and Wellington. Positive and Negative samples are indicated in red and blue respectively.

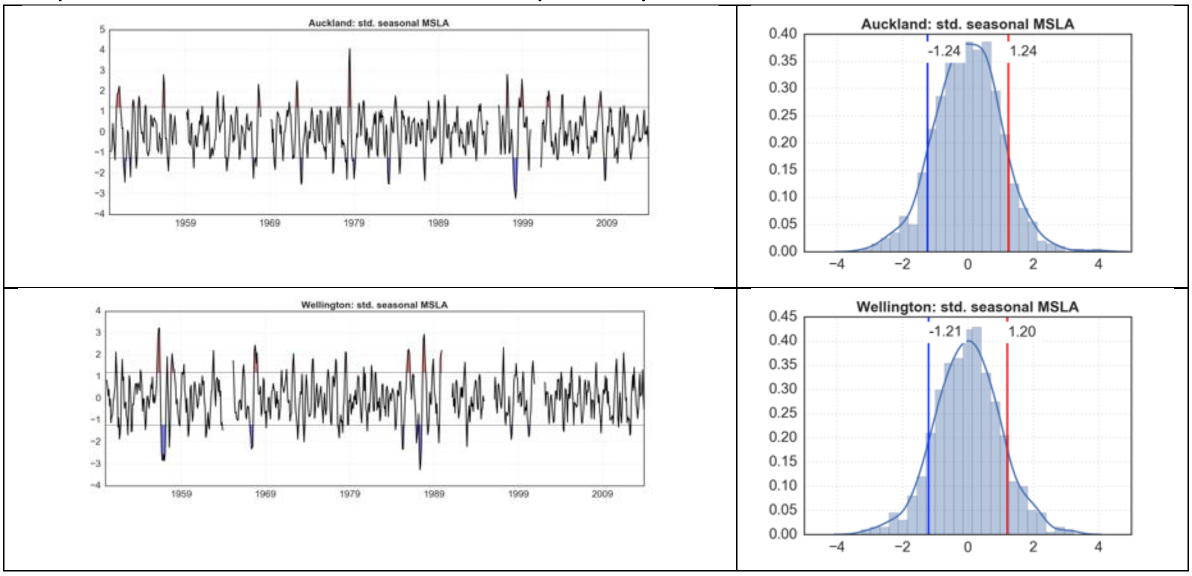


Figure C.2 *Positive and negative samples of MSLA for Auckland (top) and Wellington (bottom).*

Because of the inconsistent periods and the presence of missing values, the percentile values to define the thresholds are calculated over the whole period available and using all data available. Similarly, to ensure that one period is not over-represented, the climatology for the climate fields (SST, HGT1000, etc) is taken to cover the period spanning from the first year to the last year of the corresponding MSLA time-series: i.e. the climatology is not the same for the different composite anomaly maps. A one month lead time has been applied, so that the map shows the composite anomalies observed one month prior the corresponding increase or decrease in seasonal MSLA is observed. Figures C.3 and C.4 show the positive and negative non-linear correlations between MSLA and SST for the four long-term stations.

Caution must be exerted in interpreting these results, but the most interesting result is probably for Dunedin, for which both the negative and positive MSLA sample (i.e. seasons of higher AND lower than normal MSLA) seem to be associated (with a one month lead time) with negative SST anomalies in the central equatorial Pacific, in a pattern respectively reminiscent of 'canonical' La Niña and a more 'central Pacific' La Niña: in other words, the relationship seems strongly non-linear, with 'La Niña' patterns related to both decrease and increase in seasonal MSLA in Dunedin. This is to be compared to e.g. Auckland, for which a relatively clear symmetric pattern emerges.

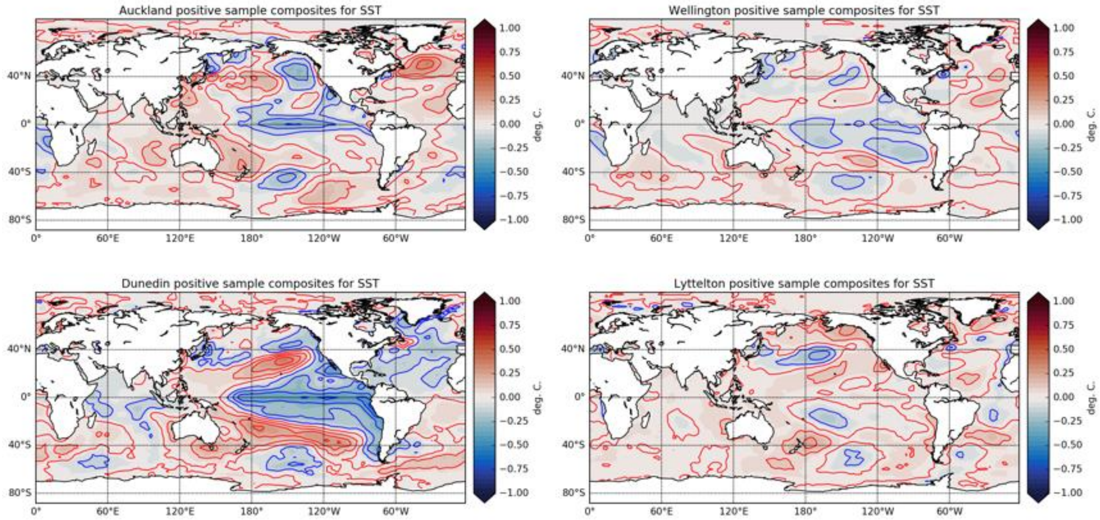


Figure C.3. *SST, positive MSLA anomaly composite.*

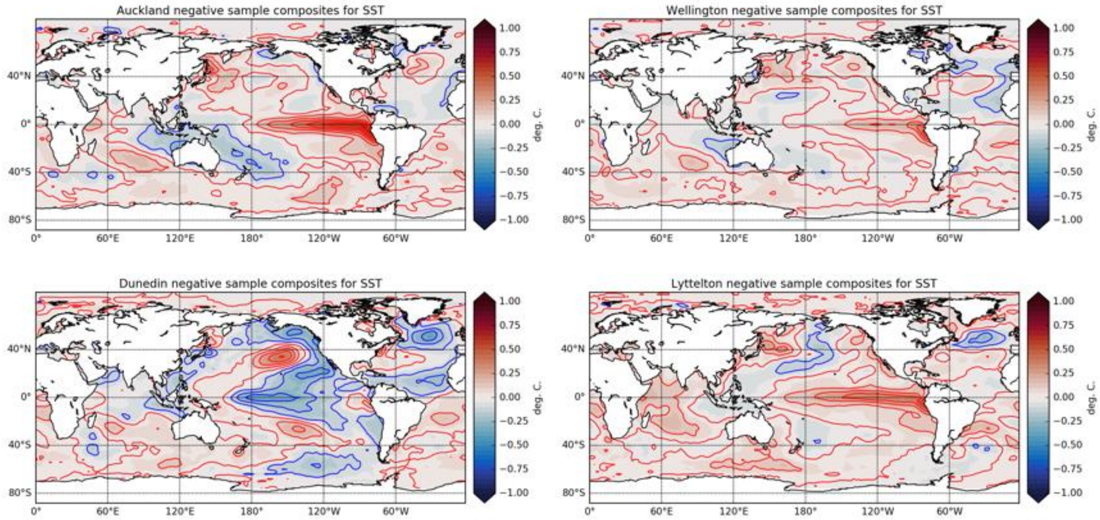


Figure C.4. *SST negative MSLA anomaly composite.*

Lead-lag correlations between MSLA and climate indices

Figure C.5 below visualises the seasonally dependent lead-lag relationships between the four long-term stations' MSLA and the NINO3.4. The white line in the middle corresponds to 0 lag: i.e. synchronous correlations, and how they vary seasonally. On the left-hand side (negative lags) are the correlations when the NINO3.4 Index leads (precedes) the MSLA time-series, while positive lags on the right-hand side show the correlations when the seasonal MSLA time-series precedes the NINO3.4 time-series. Interestingly, Lyttelton has a relatively different behaviour, the maximum negative anomalies are observed at around 1 – 0 month lead time (NINO3.4 leading) towards JJA to JAS.

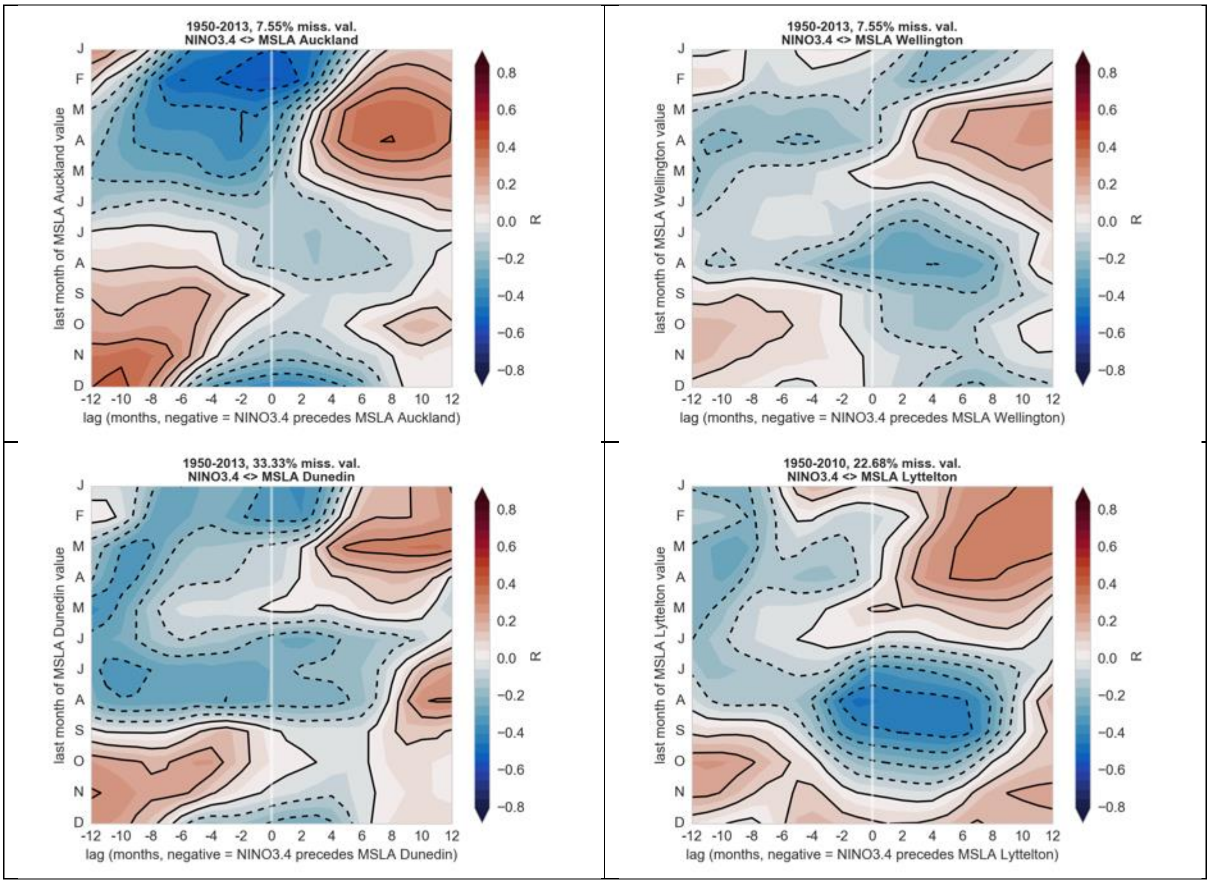


***Figure C.5**. Lead-lag relationships between MSLA and NINO3.4 (Auckland, Wellington, Lyttelton and Dunedin clockwise from top left). Dark red show strong correlations and dark blue shows strong anti-correlations.*

Coastal MSLA residual data was compared with offshore MSLA measured by satellite altimetry, data set from both the AVISO (now taken over by Copernicus (E.U. Copernicus Marine Service Information 2017)) and the PODAACS (CCAR University of Colorado Boulder 2017) were used. Correlations between the MSLA residual for the offshore and coastal data sets did not correlate particularly well – maximum correlation coefficients were only around 30%. This shows the importance of nearshore thermosteric (heating/cooling) effects to the coastal/shelf MSLA.

Appendix D: Data used in MSLA forecasting

There are four data streams that go into the MSLA forecasting, the observed MSLA calculated from observed sea surface height (historic and near real time where available), the CFSv2 forecast (available monthly), the satellite altimetry (available near real time) and the NINO3.4 SST index (calculated monthly).

Observed Sea Surface Height

The observed time-series of monthly mean sea level anomalies processed as outlined in Appendix A for stations with good data for time periods greater than 20 years were used, viz. Monthly Mean Sea Level Anomalies for Marsden Point, Auckland, Moturiki, Wellington, Lyttelton, and Dunedin. The mean seasonal cycles for these stations as calculated from historical data are used in the forecast and where data is available with less than a months or two's latency these are used for calculating the annual running mean of the sea level anomaly.

Dynamical model's forecasts of monthly Sea Surface Height

The forecasts of monthly Sea Surface Height (SSH), up to 6 months in advance, are provided by the US National Centre for Environmental Prediction (NCEP) CFSv2 (Climate Forecast System version 2) coupled General Circulation Model (Saha, Moorthi et al. 2013). CFSv2 accounts for for sea level contributions due to dynamic height, barotropic circulation, advection, and dissipation processes; using the hydrostatic equations to calculate changes in the sea surface height for each grid on the globe, but does not account for changes in ocean mass from ice-sheet melt, tectonic uplift, self-attraction and loading, glacial isostatic adjustment, land water storage, astronomical tides, surface waves, or mesoscale eddies. In other words, both the very high frequency (sub-monthly) component and the low frequency (decadal) component of sea level variations are not adequately accounted for. However, the forecasts are reasonably accurate at the monthly to inter-annual time-scales, and they can be exploited to forecast coastal monthly MSLA.

Satellite Altimetry

Delayed time (DT) and Near Real Time (NRT) satellite estimates of Sea Level Anomalies (SLA) are provided by the Copernicus Marine Environment Monitoring Service (E.U. Copernicus Marine Service Information 2017). These products are based on multi-mission satellites, and provide gridded global sea surface heights. We calculate estimates of the annual running mean sea level anomaly for each of the stations where forecasts are made and use these estimates for stations where the observed data is not available in time for the forecast.

The NINO3.4 Sea Surface Temperature index

The current state of the El Niño – Southern Oscillation (ENSO) phenomenon is captured via the NINO3.4 Sea Surface Temperature (SST) index, in the central Pacific. It consists in the average sea surface temperature anomaly in the region bounded by 5°N to 5°S, from 170°W to 120°W. It is made available in real-time by the US NOAA Climate Prediction Center (NOAA 2017).