RA:dOst
Regional Adaptation Strategies for the German Baltic Sea Coast

Future Wave Climate Projections at the German Baltic Sea Coast on the Basis of the Regional Climate Model Cosmo-CLM

KLIMZUG-Project RAdOst (2009-2014)

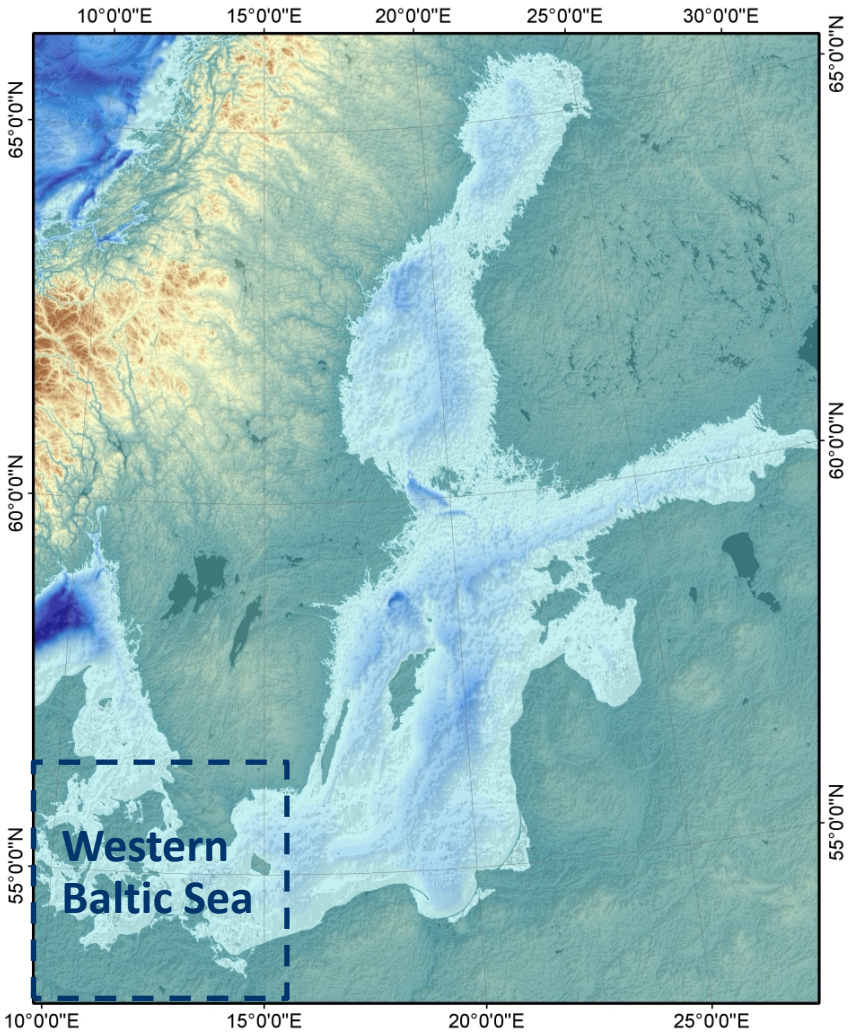
Norman Dreier (TUHH), Christian Schlamkow (Uni Rostock), Peter Fröhle (TUHH),
Dörte Salecker (TUHH) and Zhenshan Xu (Hohai University Nanjing)

SPONSORED BY THE
Federal Ministry of Education and Research

TUHH Technische Universität Hamburg-Harburg
WASSERBAU River and Coastal Engineering
Universität Rostock Traditio et Innovatio

Content

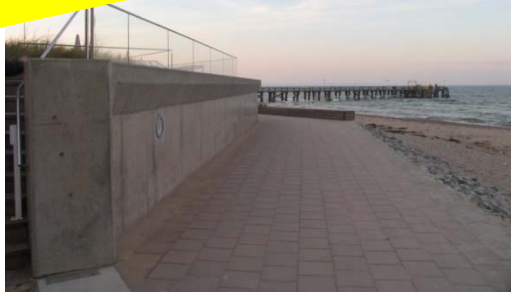
1. **Introduction**
2. **Methods**
3. **Results**
   A. Changes of Average Wave Conditions
   B. Effects of Changes of the Wave Climate
   C. Changes of Extreme Wave Heights
4. **Conclusion**



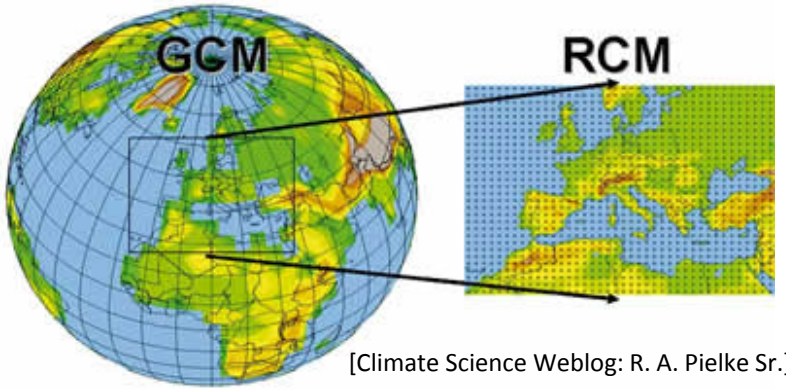
Changes of Wave Climate
and Effects of Changes ?

→ Natural Coastal Processes like e.g. Sediment Transport?
→ Effectiveness of Coastal and Flood Protection Structures?

See also Presentation "Effectiveness of Coastal and Flood Protection Structures in a Changing Climate" given by Prof. Peter Fröhle, Wednesday 09:00am!

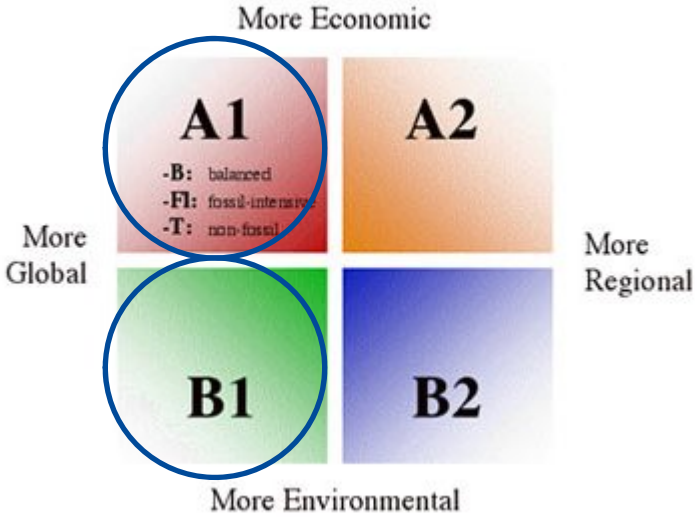


2. Methods: Wind Data



[Climate Science Weblog: R. A. Pielke Sr.]

SRES-Emission Scenarios (IPPC, AR4)



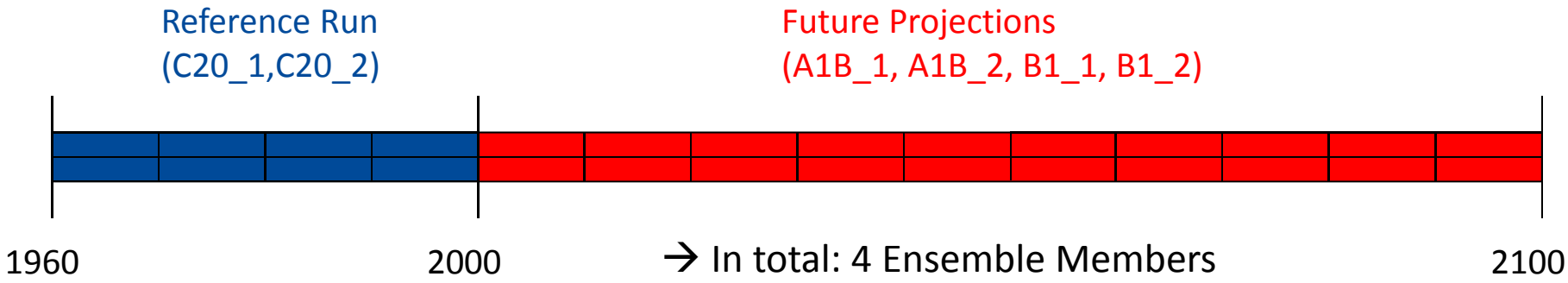
The Watson Institute for International Studies · Brown University, 2007

Cosmo-CLM (Climate Local Model) → Europe

(Rockel et al., 2008; Lautenschlager et al., 2009)

Forcing: AOGCM ECHAM5/MPI-OM

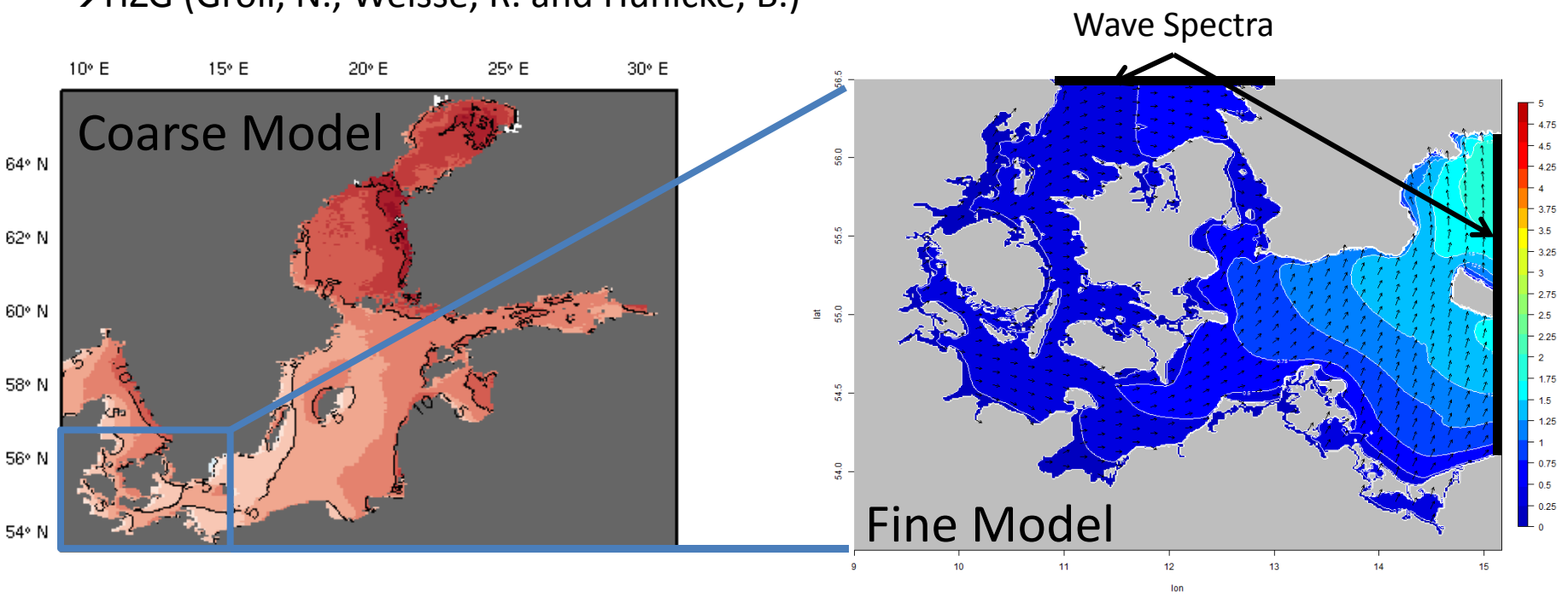
Horizontal-, Time resolution: 0.2/0.165° ,1hr



2. Methods: Numerical Simulations (Nesting of SWAN in WAM)

Baltic Sea (WAM, Hasselmann et al., 1988)
→HZG (Groll, N., Weisse, R. and Hünicke, B.)

Western Baltic Sea (SWAN, Booij et al., 1999)



5.5km, 35 Frequencies, 24 Directions

1.1km, 42 Frequencies, 144 Directions

Temporal resolution: 1hr
Time domain: 1960-2100

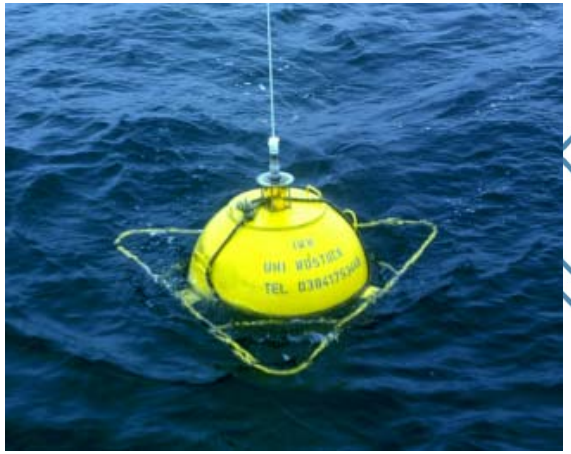
parallel computation on high performance multi-processor clusters

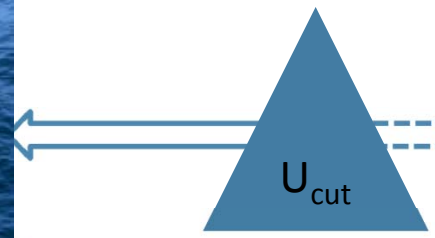
DKRZ: German Climate Computing Centre

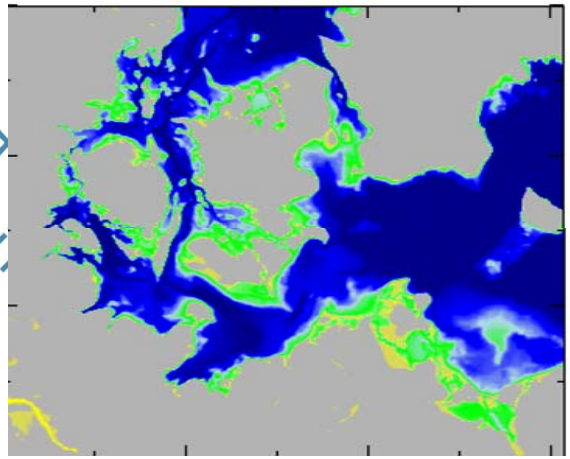
Computing Centre of TUHH resp. UR

Statistical Correlation Wind↔Waves
From measurements at specific locations
[Fröhle & Fittschen 1999; Fröhle 2000]

Stationary Numerical simulations:
SWAN [Booij et al., 2009]
$\Delta U=1m/s$, $\Delta \Theta_w=10°$

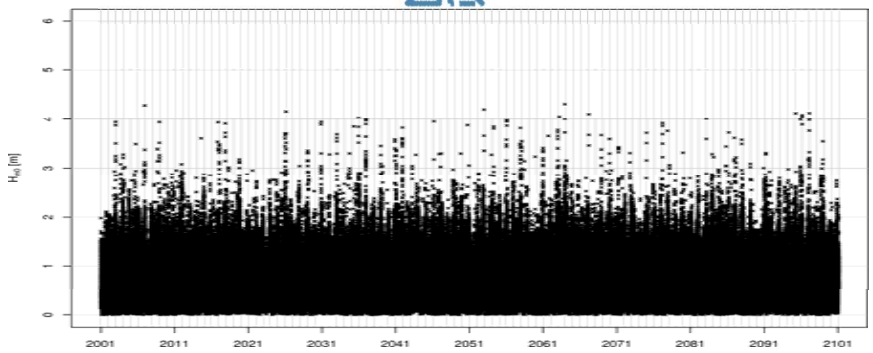






~ 97%

~ 3%



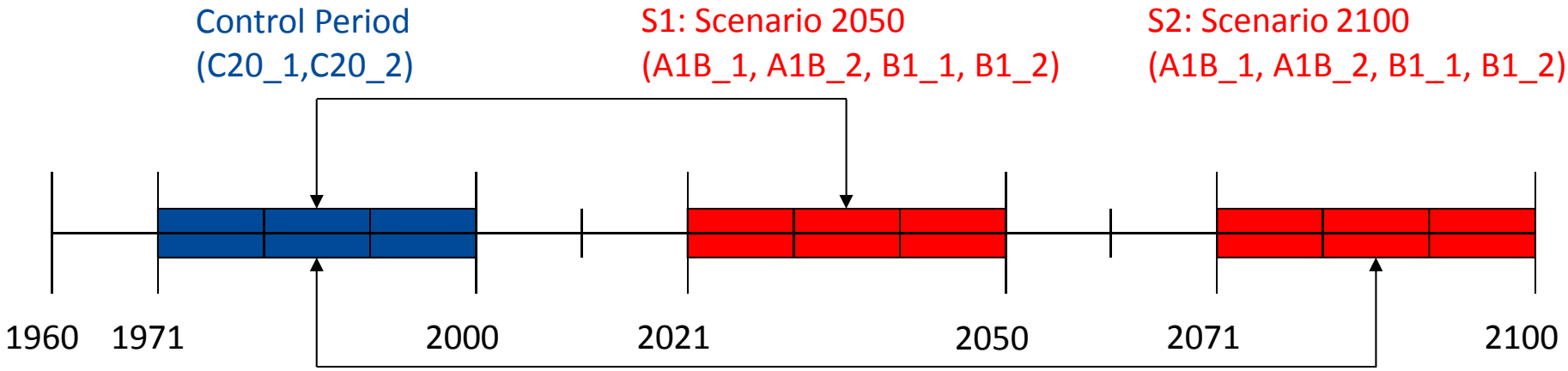
4 Long-term time series of wave parameters

(1960-2100)

At specific Locations!

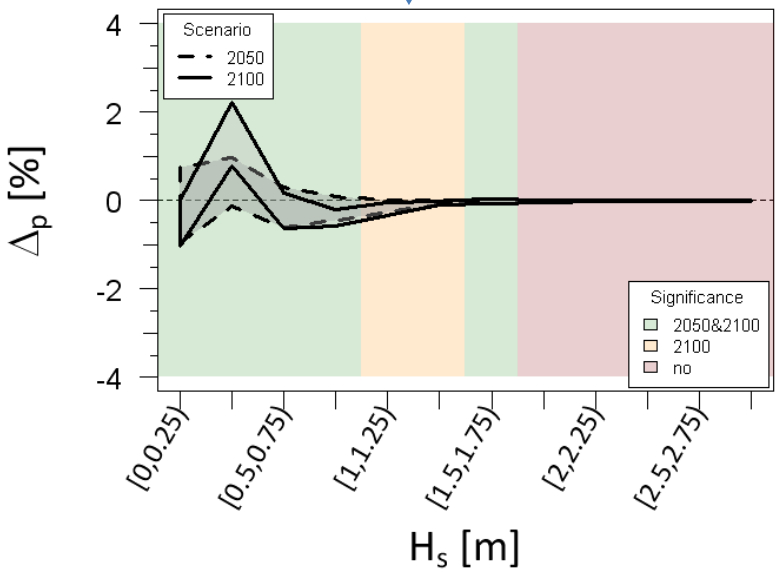
Comparisions of Frequency of Occurrence and Average Values of Wave Parameters for the Scenarios A1B and B1 (2050, 2100)

- ➔ Values for Control Period C20 (1971-2000 resp. 1961-1990)
- ➔ Timeperiods of 30 years
- ➔ Annual (∅) and Seasonal Averages (DJF, MAM, JJA, SON)

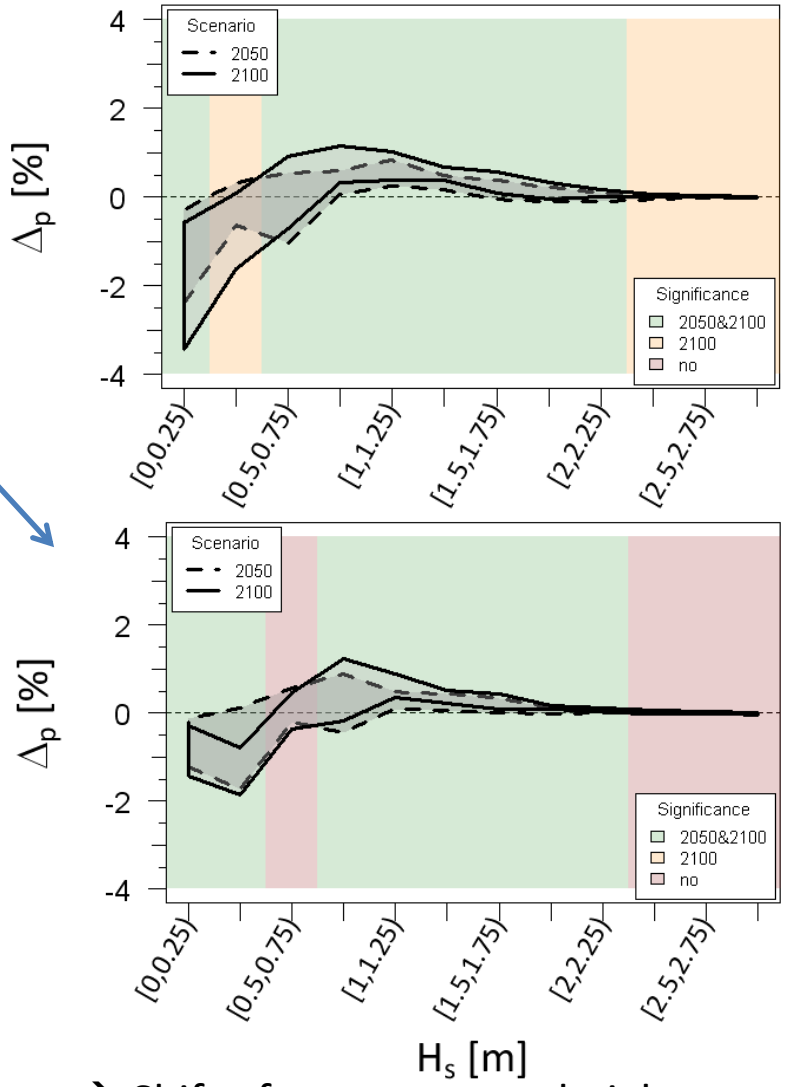


→ Signficant Wave Heights, Mean Wave Periods and Mean Wave Directions

3. Results: A) Changes of Average Wave Conditions – Frequency of Sign. Wave Heights



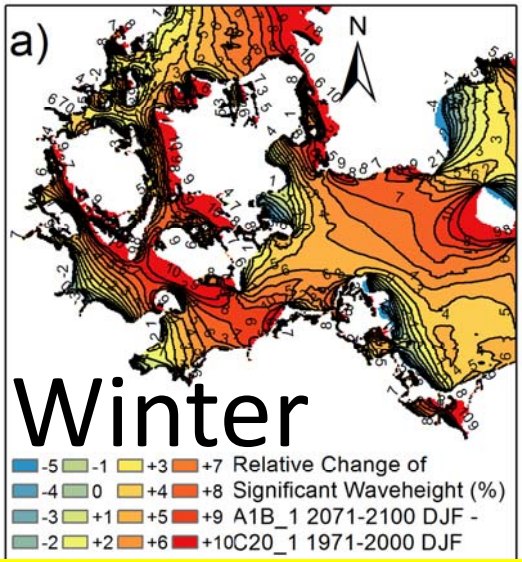
→ Spatial and Temporal Variability!

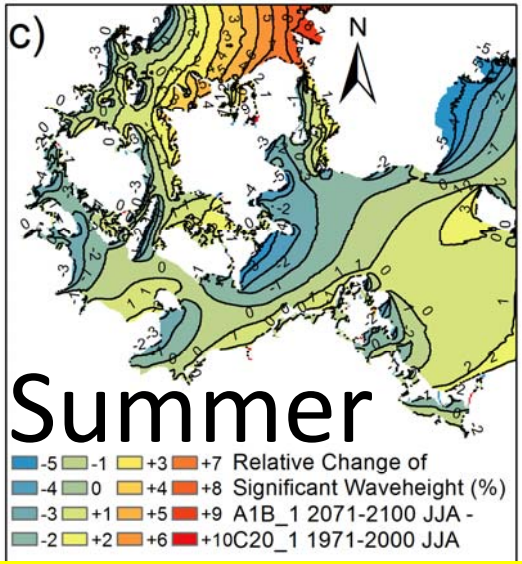


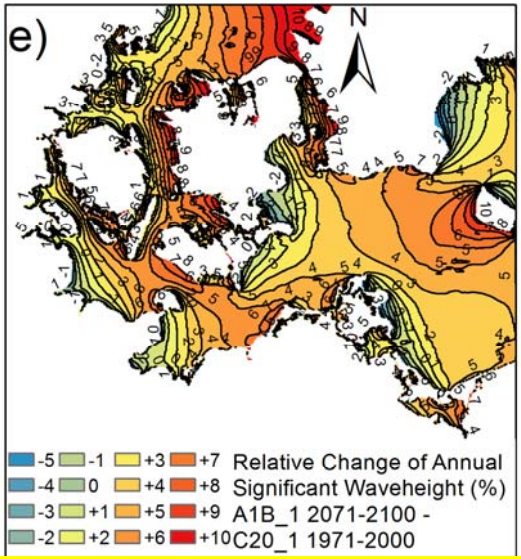
→ Shift of average wave heights towards higher/lower values!

Parametric Hypothesis Tests
Significance Level 0.05

3. Results: A) Changes of Average Wave Conditions – Averages of Sign. Wave Heights



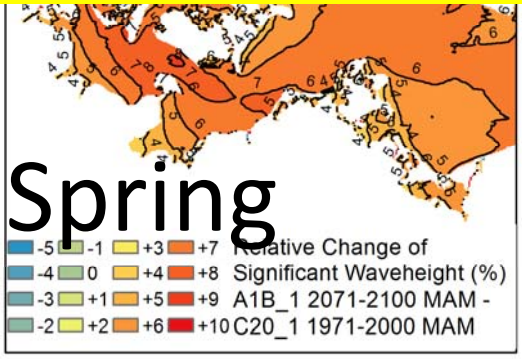


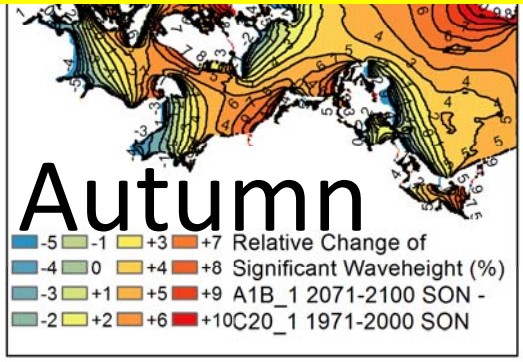


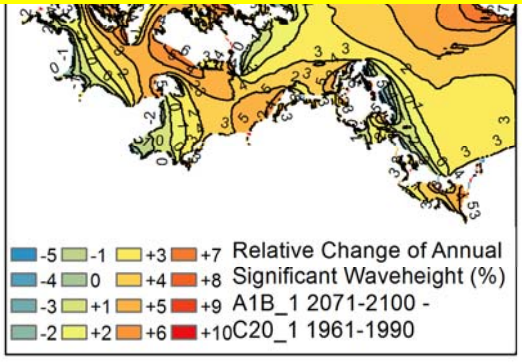
Total Bandwith of Changes:

W: -2% to +10.3%, higher values predominant.

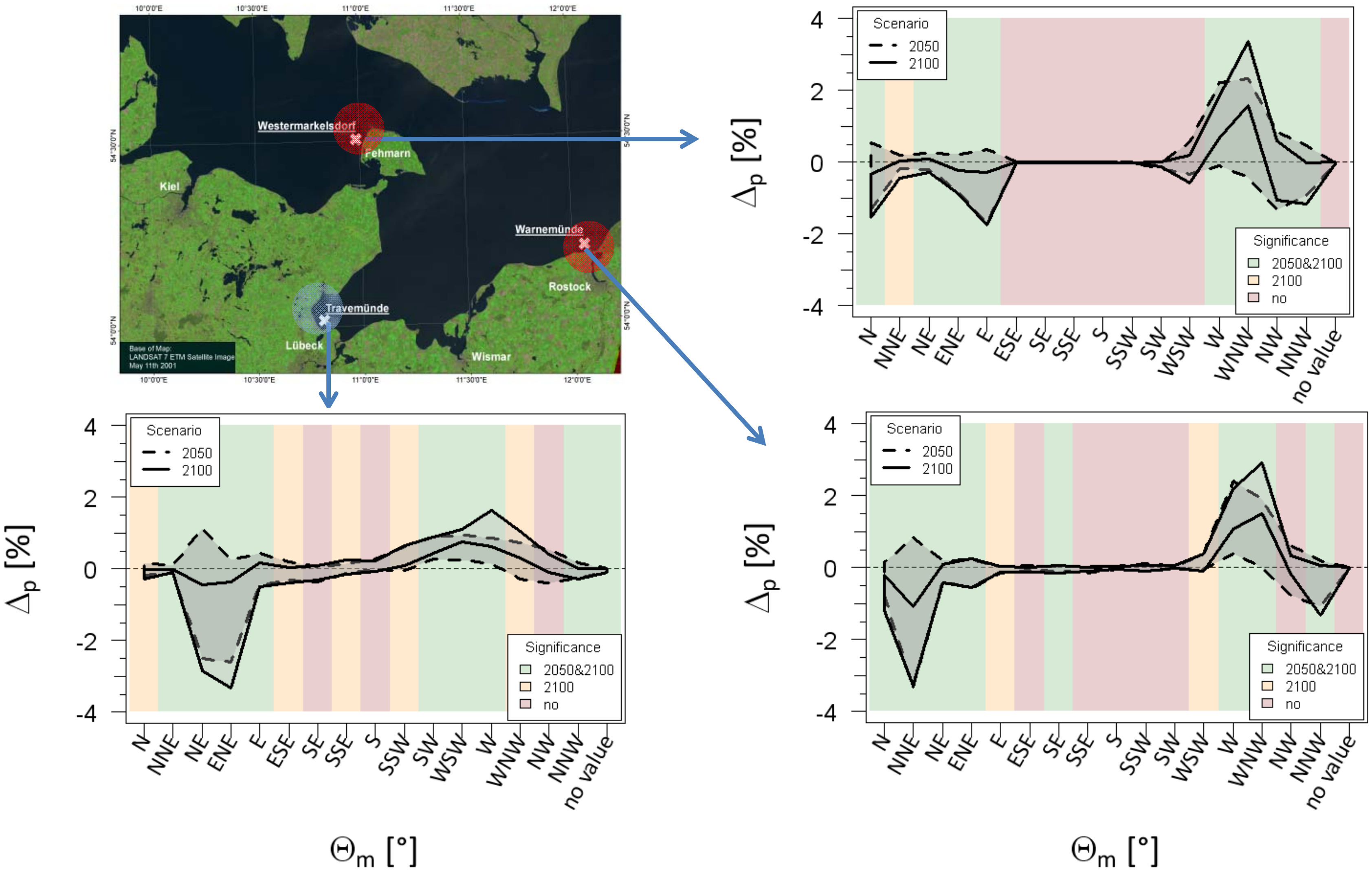
E: -5.7% to +5.3%, lower and higher values possible!







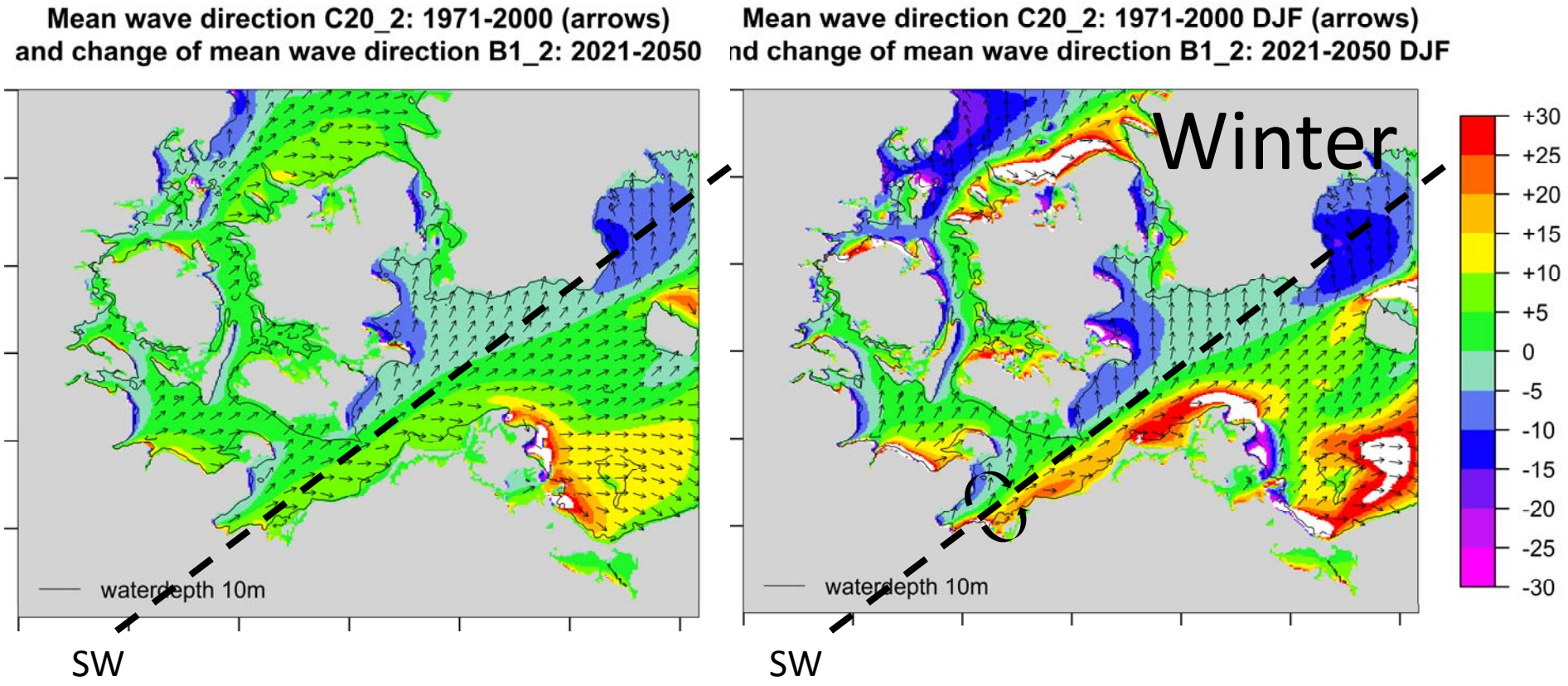
3. Results: A) Changes of Average Wave Conditions – Frequency of Mean Wave Direct.



→ Spatial and Temporal Variability!

→ Shift of average wave directions towards westerly directions!

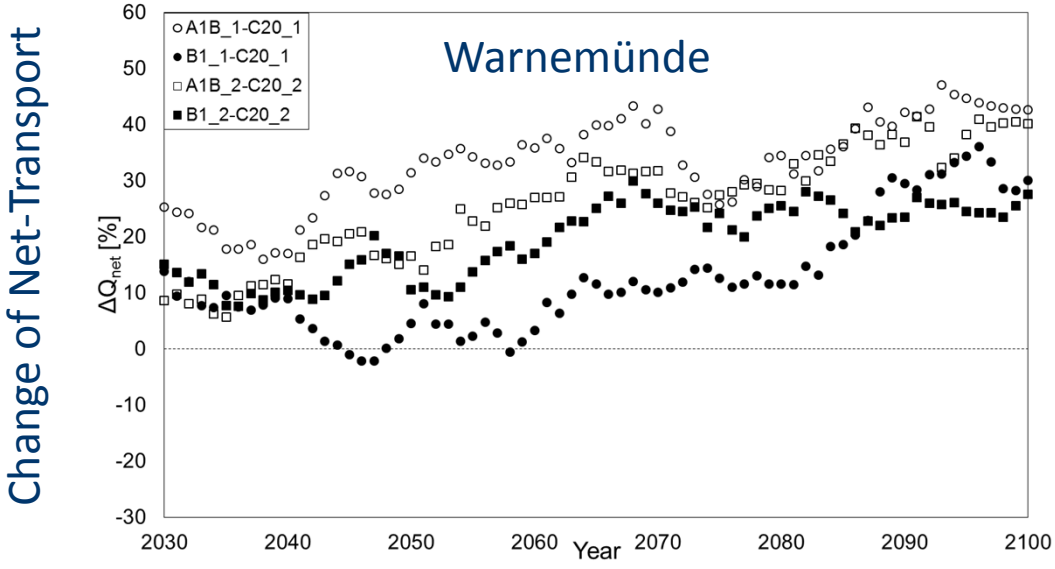
Absolute Changes of Averages of Mean Wave Directions (in Degree)
- Mathematical defintion of rotation -



Bandwith of Annual Changes: up to +10°

Bandwith of Seasonal Changes: up to +30°

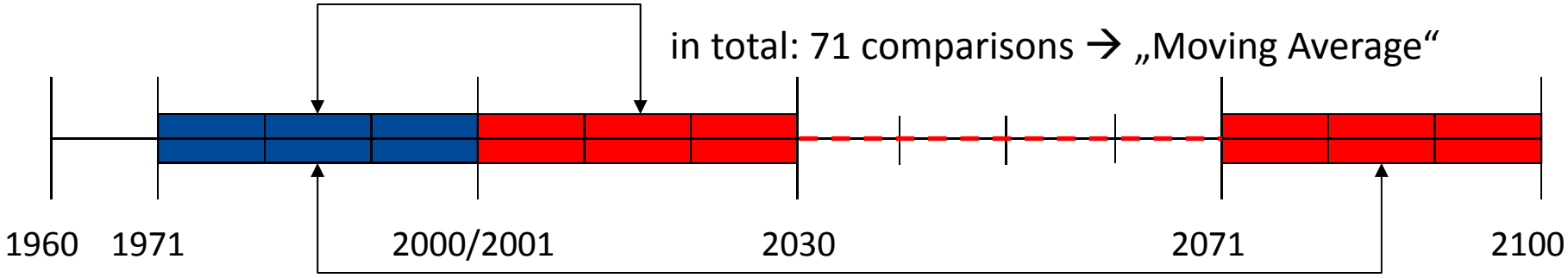
Calculation of long-shore transport capacities, CERC approach
→ Genesis (Hanson, 1989)



Control Period
(C20_1,C20_2)

S1: Scenario 2030
(A1B_1, A1B_2, B1_1, B1_2)

S71: Scenario 2100
(A1B_1, A1B_2, B1_1, B1_2)

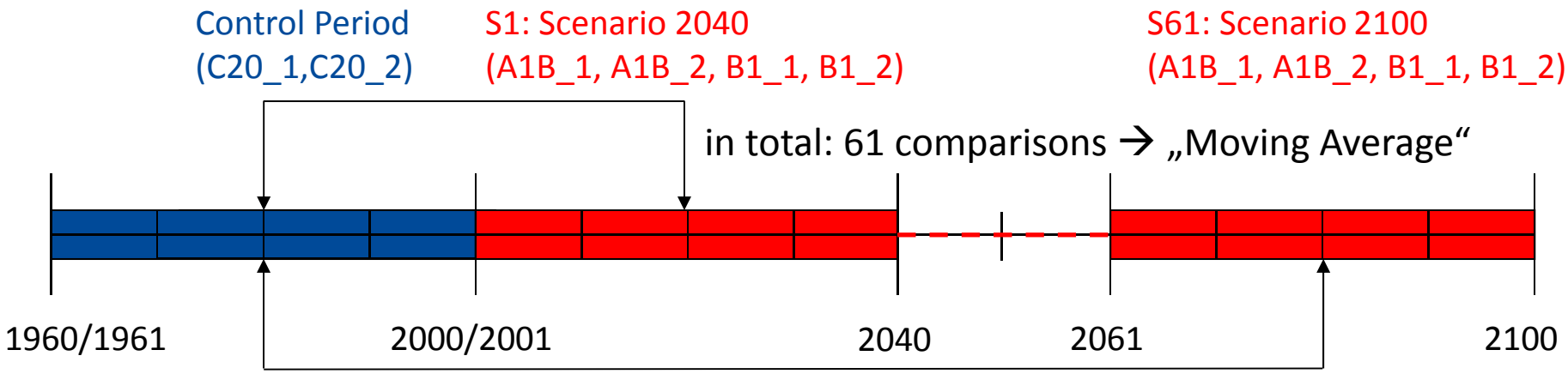


(1) Sample Selection: annual maximum significant wave heights, 40 years

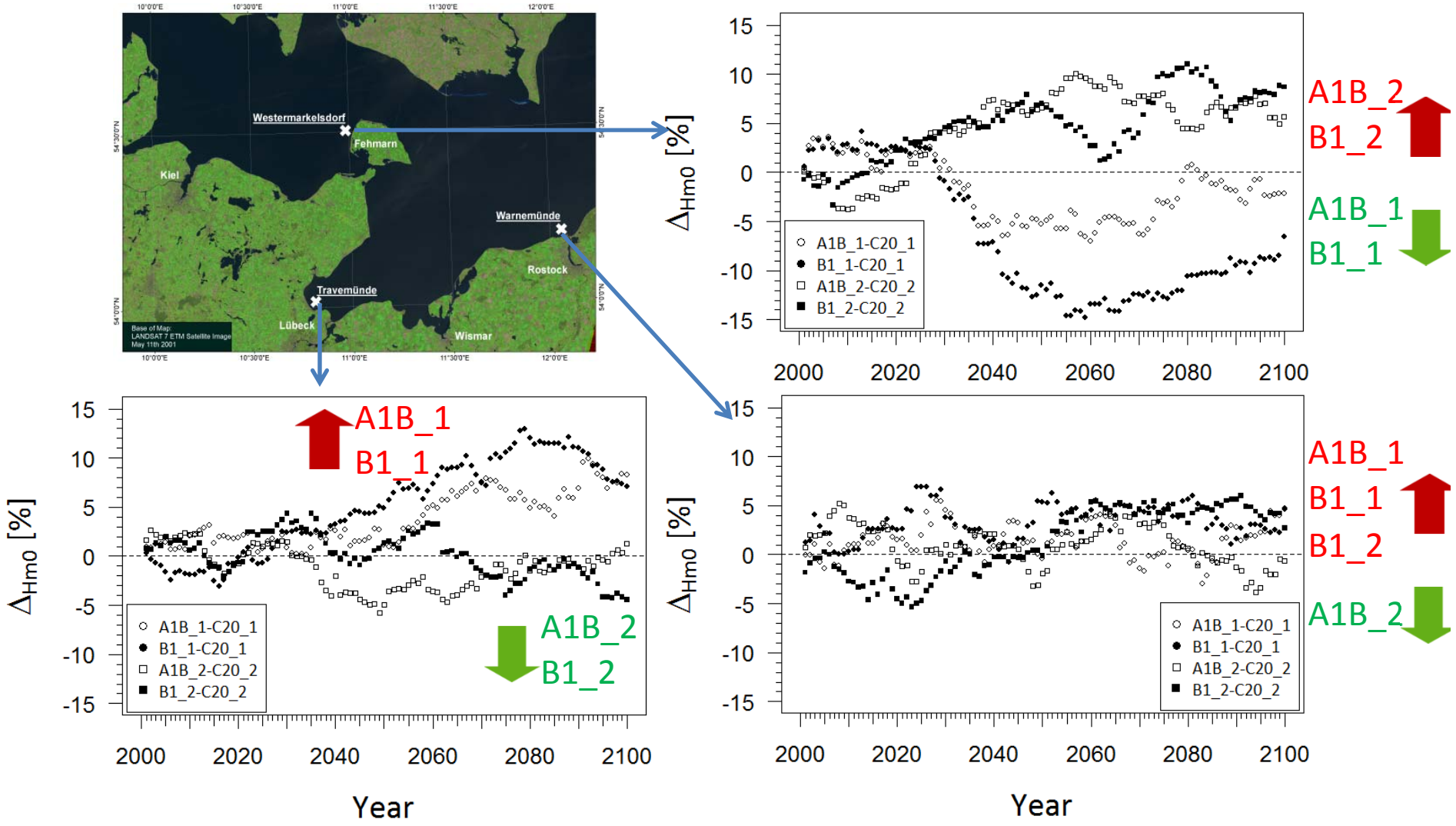
(2) Fitting : Distributions Gumbel, Weibull, Log-Normal and GEV (MLE)

(3) Goodness of fit-tests* (D_{max} resp. D_{rms} between empirical & theoretical CDF)
→ Log-Normal

(4) Calculation of extreme wave heights, return-period 200 years



3. Results: C) Changes of Extreme Wave Events → Extreme Value Analysis



→ Strong Spatial and Temporal Variability!

4. Conclusion

- ECHAM5/MPI-OM + Cosmo-CLM (A1B, B1):
  - → Changes of frequency (higher wind velocities, more westerly winds)

- Changes of Average Wave Conditions:
  - → Changes of frequency (higher/lower values, more westerly events)
  - → Prominant at W/NW wind exposed locations
    - ❖ Significant wave heights (up to +10%)
    - ❖ Mean wave periods (up to +4%, not shown here)
    - ❖ Mean wave directions (up to +30°)
  - → High spatial, seasonal and temporal variability
  - → Consequences for the sediment transport and functional design of coastal protec tion structures

- Changes of Extreme Wave Events:
  - → Large Bandwith: +15% to -15%
  - → No clear tendency
  - → Consequences for the constructional design of coastal protection structures

4. Conclusion

- Comparison of Approaches

  → Good Agreement of Results using Different Methods for the Calculation of the Wave Climate

  → Hybrid approach fast and efficient, but limited to locations with wave measurements!

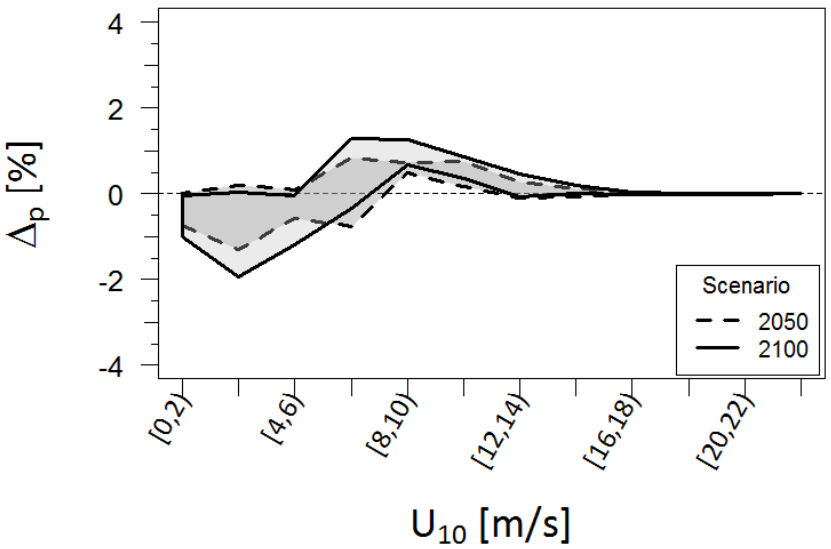
- Future Work

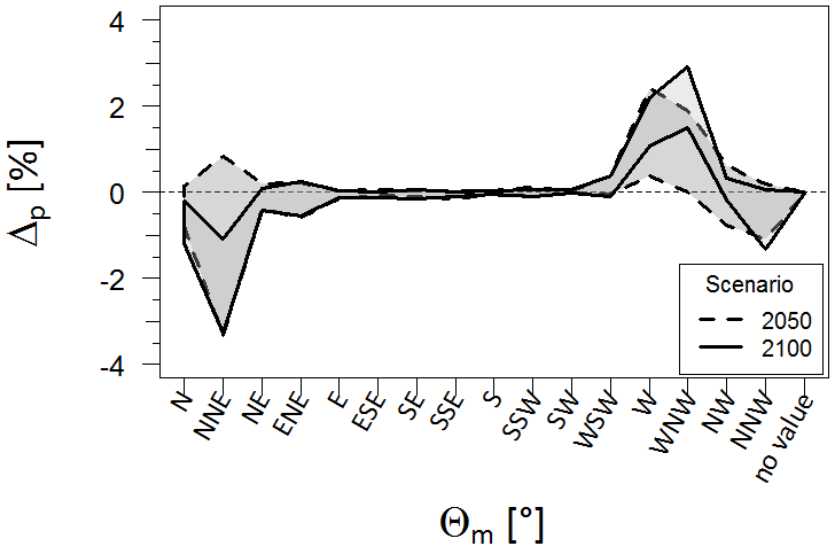
  → Extend ensemble of projections: transient hight resolution regional climate model data (down to 11km) from different global forcing models (e.g. HadCM3)

Thank you for your kind attention!

Veränderung der mittleren Windverhältnisse

Abb.: Bandbreite der Veränderung der Häufigkeiten für die Windgeschwindigkeit (li.) und Windrichtung (re.), Warnemünde im Vergleich zum Vergleichszeitraum 1971-2000



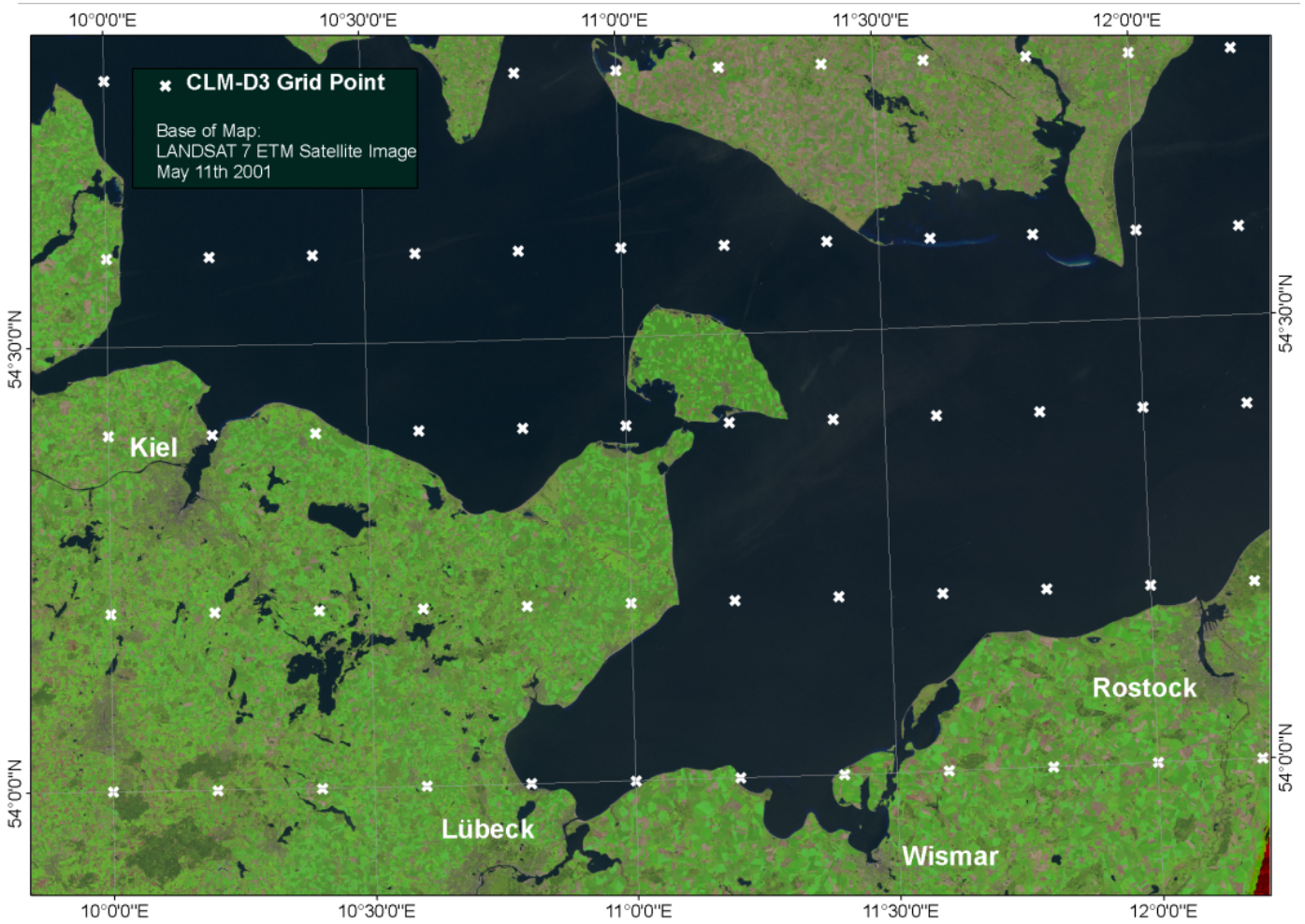


- Signifikante Veränderung der Häufigkeitsverteilung hin zu höheren Windgeschwindigkeiten
  → Zunahme der Mittelwerte
- häufiger westliche und nordwestliche Richtungen
- seltener nördliche und nordöstliche Richtungen
  → geringe Veränderung der Mittelwerte zu westlichen Richtungen

Minimale und Maximale Veränderung	Mittlere Windgeschwindigkeit		Mittlere Windrichtung	
Auswertungszeitraum	2021-2050	2071-2100	2021-2050	2071-2100
Warnemünde	+2% - +3%	+2% - +4%	- 3° - +9°	+1° - +9°
Travemünde	+1% - +2%	+2% - +4%	-2° - +9°	+1° - +8°
Westermarkelsdorf (Fehmarn)	+2%	+2% - +4%	-1° - +11°	+2° - +11°

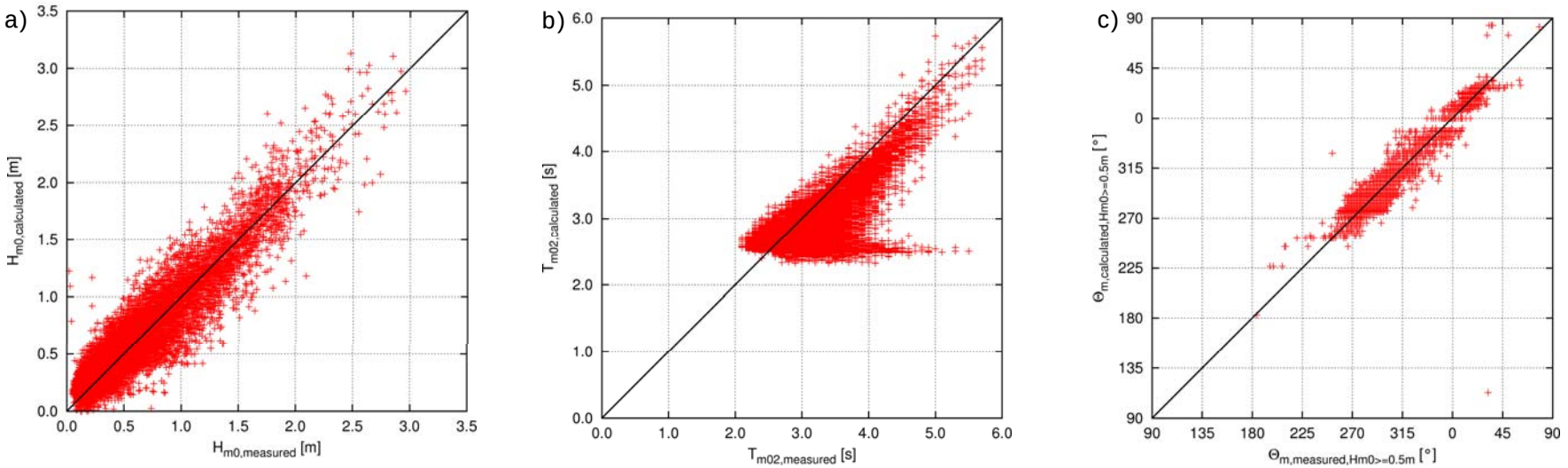
Trend zur Zunahme und Veränderung zu mehr westlichen Windrichtungen

Cosmo-CLM Grid of Dataset 3



- No BIAS-Correction
- Bilinear Interpolation to horizontal resolution of the wave model (approx. 1km)

Validation of Wind Wave Correlations



Calculated and observed wave heights (a) wave periods (b) and wave directions for significant wave heights > 0.5m (c), location Warnemünde

	$\lvert\Delta H_{m0}\rvert$ [m]	$\lvert\Delta T_{m02}\rvert$ [s]	$\lvert\Delta \Theta_w\rvert$ [°]
Warnemünde	0.10473	0.44819	6.48415
Travemünde	0.08785	0.45050	7.44012
Wester-markelsdorf	0.07481	0.21654	7.01464

Mean absolute deviations between calculated and measured values at the locations of the example areas

Correction of Time Series of Wave Parameters

Problem:

Correlation valid within certain error margin

Goal:

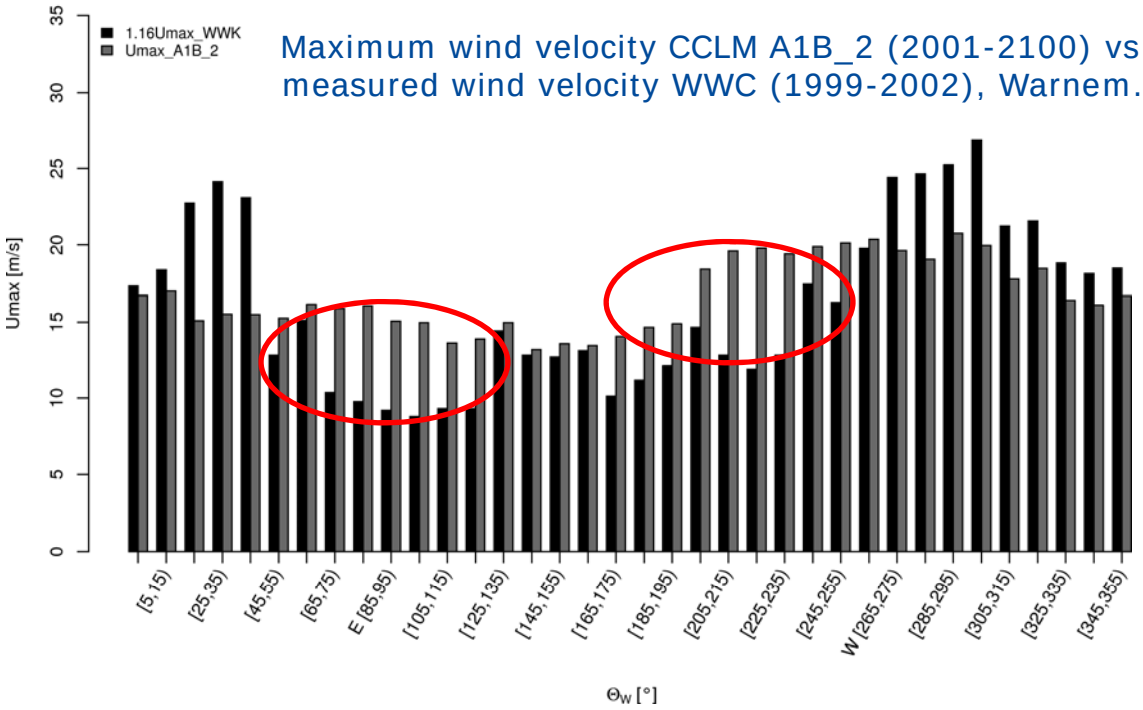
Improvement of accuracy of calculated wave heights (extreme value analysis)

Cut-off criteria:

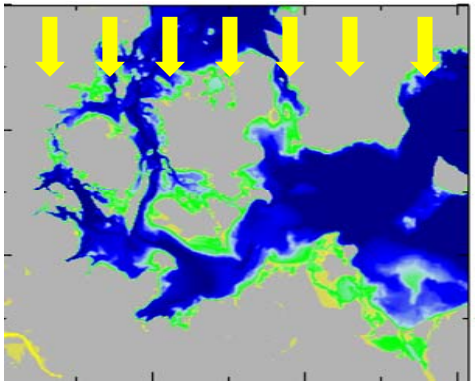
$U_{cut,CLM}=1.16*U_{max,WWK}$

(5% error margin)

[Fröhle & Fittschen, 1999]



Maximum wind velocity CCLM A1B_2 (2001-2100) vs. measured wind velocity WWC (1999-2002), Warnem.



➔ SWAN: stationary mode

simplification: constant wind field over the area

resolution of wind boundary: $\Delta U_{10}=1m/s$, $\Delta \Theta_w=10°$

Statistical Significance of Changes of Average Wave Conditions

Approach: Significance test of differences of frequencies of occurrence
=parametrical Test (z-Test), assumption: normal distribution

(I) Null-Hypothesis: $H_0: p_A = p_B$ Alternative Hypothesis: $H_1: p_A \neq p_B$

(II) Standard error of differences of freq. $$STDERR_{A,B} = \sqrt{\frac{p_A(1-p_A)}{N_A} + \frac{p_B(1-p_B)}{N_B}}$$

(III) z-value: $$z_{calc} = \frac{p_A - p_B}{STDERR_{A,B}}$$

(IV) critical z-value: from e.g. table of the normal distribution or calculation with R-Software

$$\alpha = 0.05 \qquad z_{crit} = q.norm(\alpha) \approx 1.65$$

(V) Comparison:

$z_{calc} \geq z_{crit}$ Rejection of H_0 and acceptance of H_1
➔ Change of freq. is stat. **significant** at given level of sign.

$z_{calc} < z_{crit}$ H_0 can not be rejected
➔ Change of freq. is stat. **not significant**

Statistical Significance of Changes of Average Wave Conditions

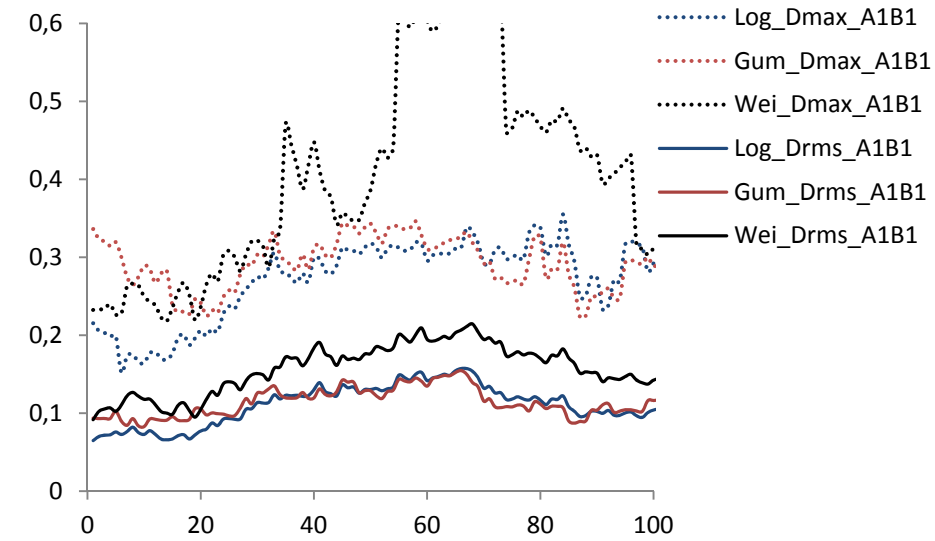
Tables of the Normal Distribution

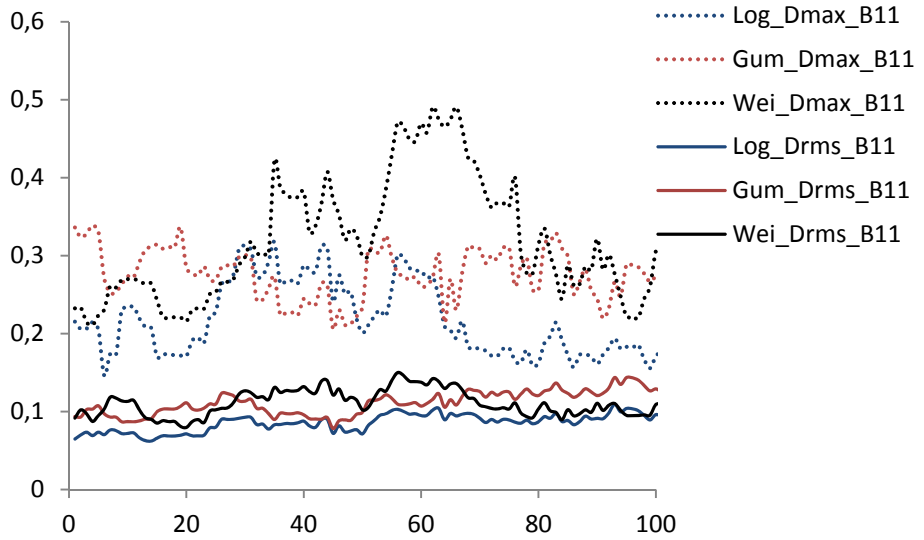
Probability Content from -oo to Z

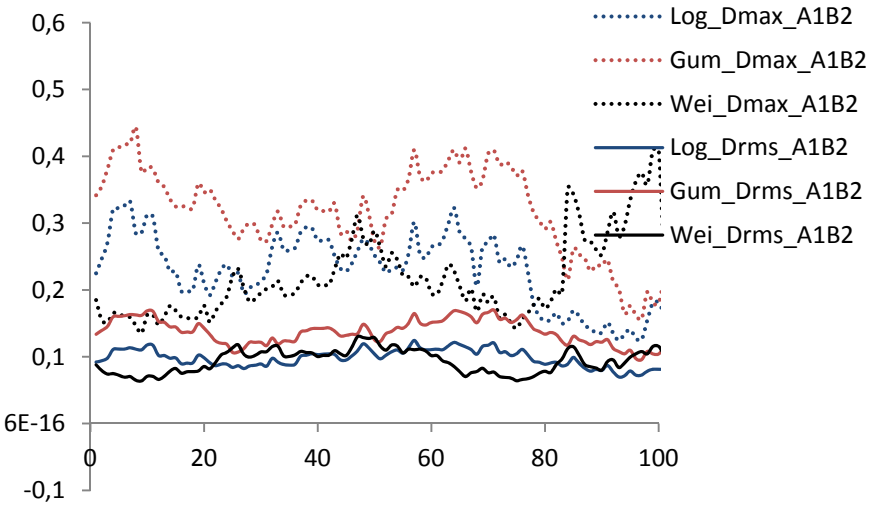
Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9987	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990

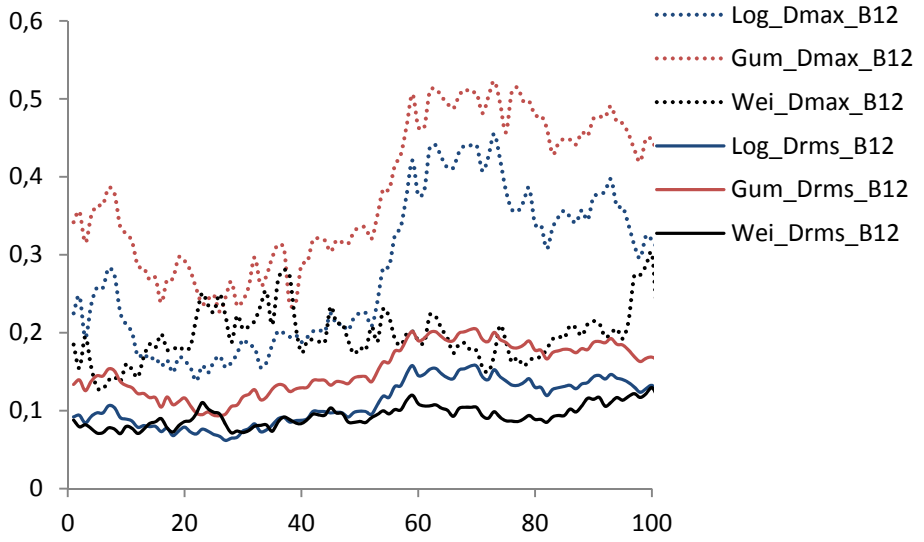
$z_{crit} \sim 1.65$

Goodness of fit Tests (Dmax, Drms) – Warnemünde → Log-Normal (Drms)



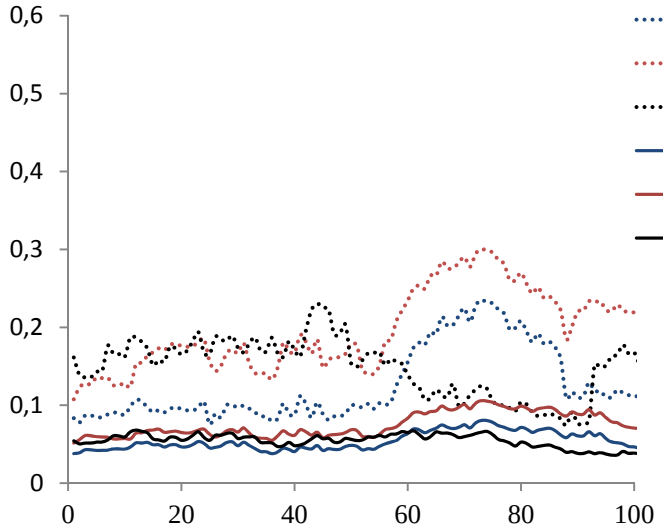


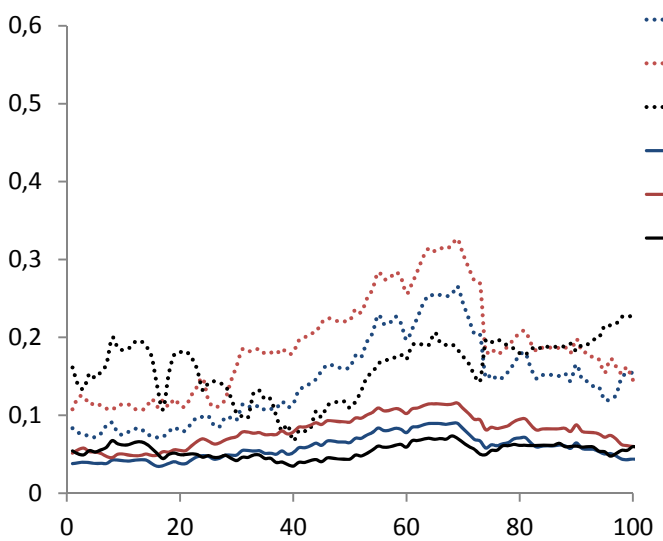


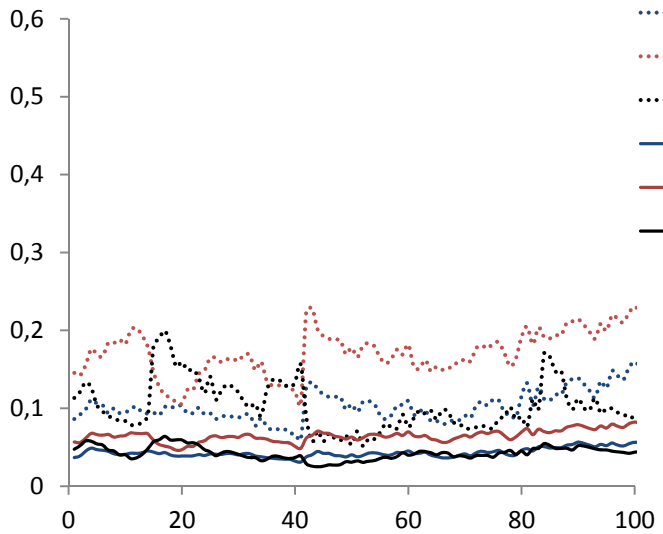


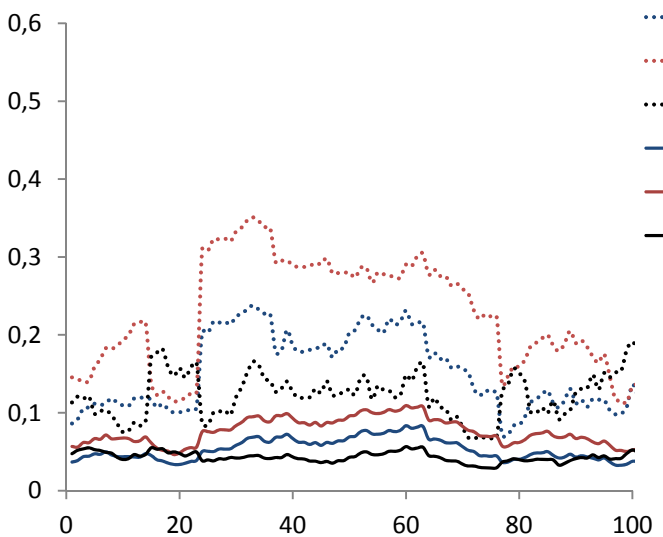
[Zhan-shan Yu, College of Harbor, Coastal and Offshore Engineering, Hohai University, Nanjing, 210098 China]

Goodness of fit Tests (Dmax, Drms) – Travemünde → Weibull/Log-Normal (Drms)



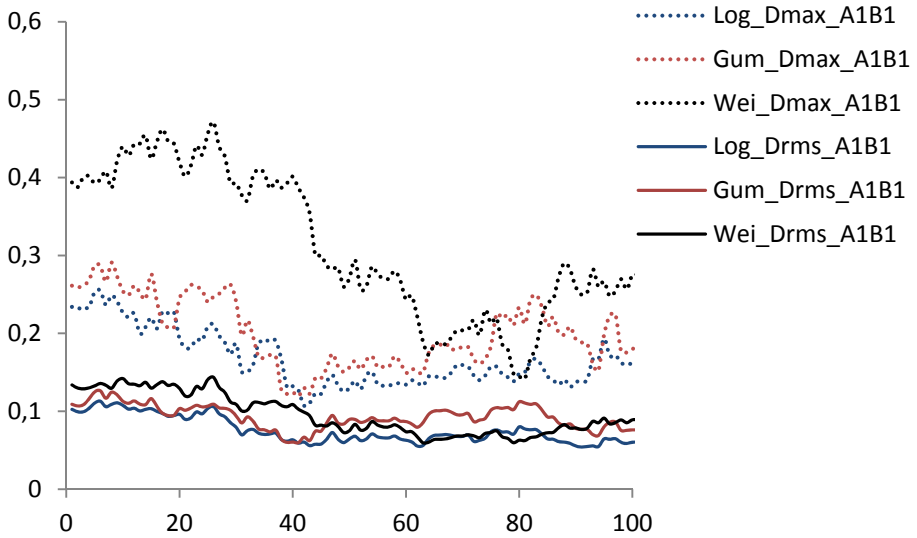


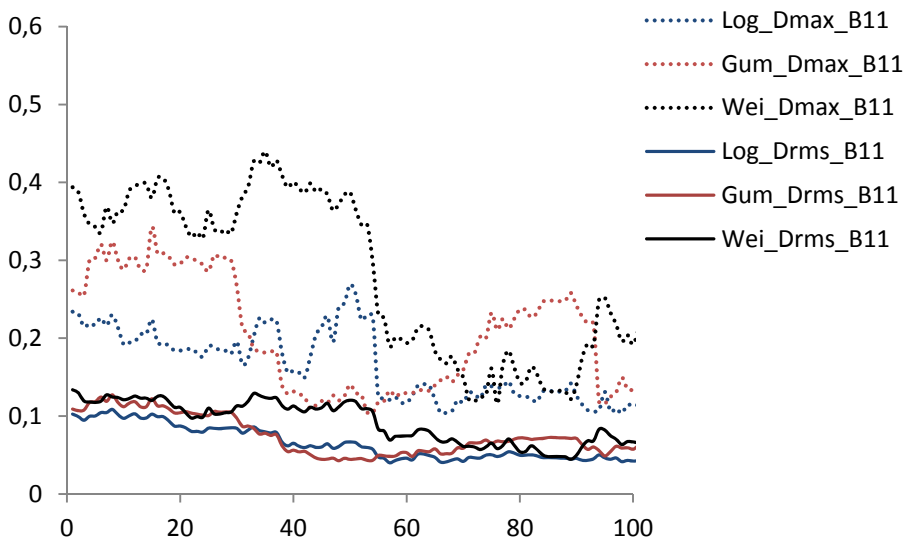


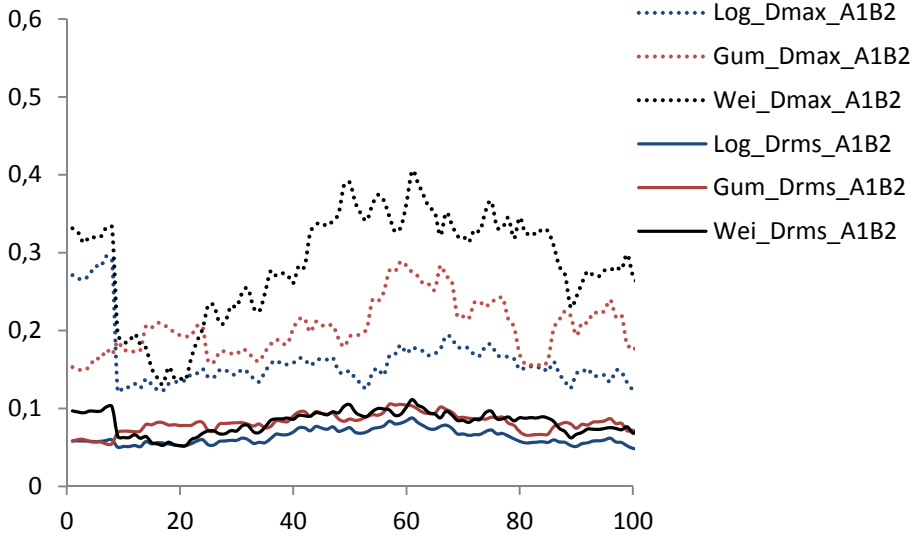


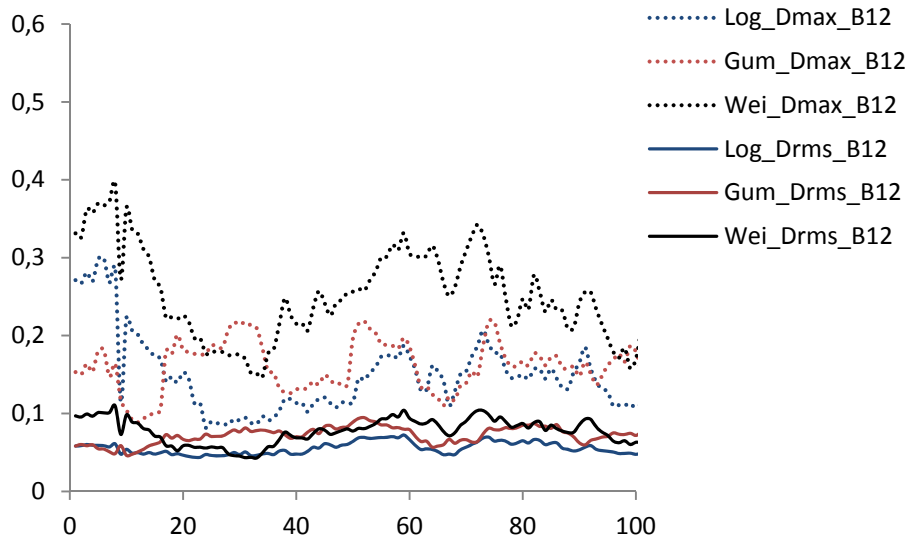
[Zhan-shan Yu, College of Harbor, Coastal and Offshore Engineering, Hohai University, Nanjing, 210098 China]

Goodness of fit Tests (Dmax, Drms) – Westermarkelsdorf → Log-Normal (Drms)









[Zhan-shan Yu, College of Harbor, Coastal and Offshore Engineering, Hohai University, Nanjing, 210098 China]

3. Results: 1) Changes of Average Wave Conditions – Wave Heights

Average Significant Wave Heights - Warnemünde						
Run	Period	∅ [m]	DJF [m]	MAM [m]	JJA [m]	SON [m]
C20_1	1971-2000	0.4712	0.5169	0.3916	0.4604	0.5173
C20_2	1971-2000	0.4748	0.5215	0.4049	0.4474	0.5267
A1B_1	2071-2100					
A1B_1	2021-2050					
A1B_2	2071-2100					
A1B_2	2021-2050					
B1_2	2071-2100					
B1_2	2021-2050					
B1_1	2071-2100					
B1_1	2021-2050					

Relative Changes of Average Significant Wave Heights - Warnemünde						
Run	Period	∅ [%]	DJF [%]	MAM [%]	JJA [%]	SON [%]
A1B_1	2071-2100	5.9	8.2	6.8	1.0	7.4
A1B_1	2021-2050	4.3	1.6	10.3	0.9	5.3
A1B_2	2071-2100	5.3	4.5	4.4	5.6	6.7
A1B_2	2021-2050	2.8	7.6	1.8	2.2	-0.6
B1_2	2071-2100	3.5	-0.3	4.8	7.2	3.2
B1_2	2021-2050	1.9	-2.0	3.7	4.1	2.3
B1_1	2071-2100					
B1_1	2021-2050					
Minimum	2100	3.5	-0.3	4.4	1.0	3.2
Maximum	2100	5.9	8.2	6.8	7.2	7.4
Minimum	2050	1.9	-2.0	1.8	0.9	-0.6
Maximum	2050	4.3	7.6	10.3	4.1	5.3
Minimum	2050,2100	1.9	-2.0	1.8	0.9	-0.6
Maximum	2050,2100	5.9	8.2	10.3	7.2	7.4

Bandwith of Changes:
-2% to +10.3%
(appr. 0.05m)

Higher values predominant

3. Results: 1) Changes of Average Wave Conditions – Wave Heights

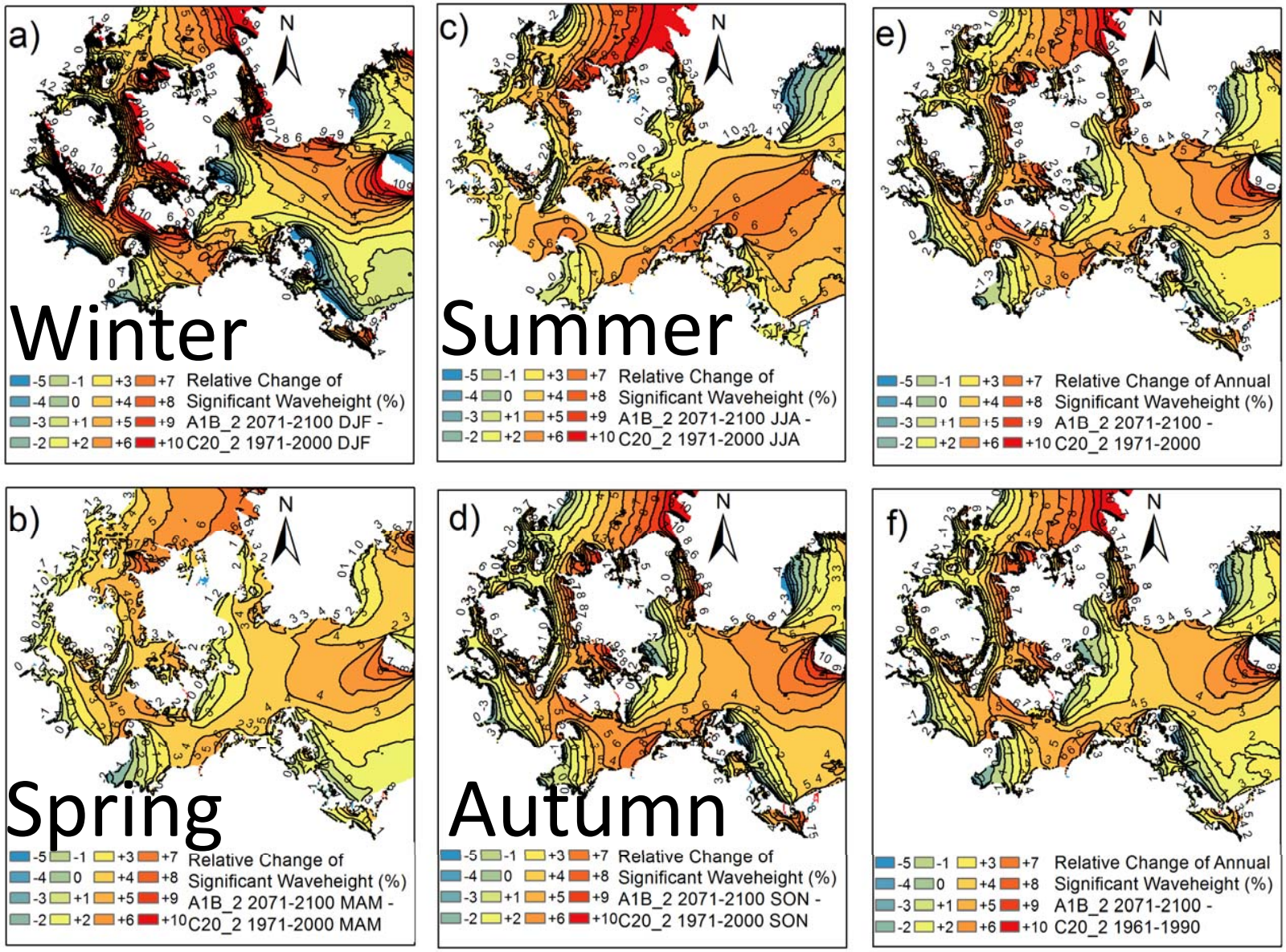
Average Significant Wave Heights - Travemünde						
Run	Period	∅ [m]	DJF [m]	MAM [m]	JJA [m]	SON [m]
C20_1	1971-2000	0.3095	0.3495	0.3074	0.2698	0.3121
C20_2	1971-2000	0.3120	0.3531	0.3247	0.2642	0.3068
A1B_1	2071-2100					
A1B_1	2021-2050					
A1B_2	2071-2100					
A1B_2	2021-2050					
B1_2	2071-2100					
B1_2	2021-2050					
B1_1	2071-2100					
B1_1	2021-2050					

Relative Changes of Average Significant Wave Heights - Travemünde						
Run	Period	∅ [%]	DJF [%]	MAM [%]	JJA [%]	SON [%]
A1B_1	2071-2100	-0.9	-2.0	3.8	-1.0	-4.4
A1B_1	2021-2050	-1.0	-4.8	5.3	-0.8	-3.3
A1B_2	2071-2100	-1.9	-4.4	-1.9	0.6	-1.3
A1B_2	2021-2050	-0.3	-2.9	2.6	1.0	-1.5
B1_2	2071-2100	-1.2	-5.7	1.2	1.2	-0.8
B1_2	2021-2050	-0.4	-4.4	-0.7	3.3	1.4
B1_1	2071-2100					
B1_1	2021-2050					
Minimum	2100	-1.9	-5.7	-1.9	-1.0	-4.4
Maximum	2100	-0.9	-2.0	3.8	1.2	-0.8
Minimum	2050	-1.0	-4.8	-0.7	-0.8	-3.3
Maximum	2050	-0.3	-2.9	5.3	3.3	1.4
Minimum	2050,2100	-1.9	-5.7	-1.9	-1.0	-4.4
Maximum	2050,2100	-0.3	-2.0	5.3	3.3	1.4

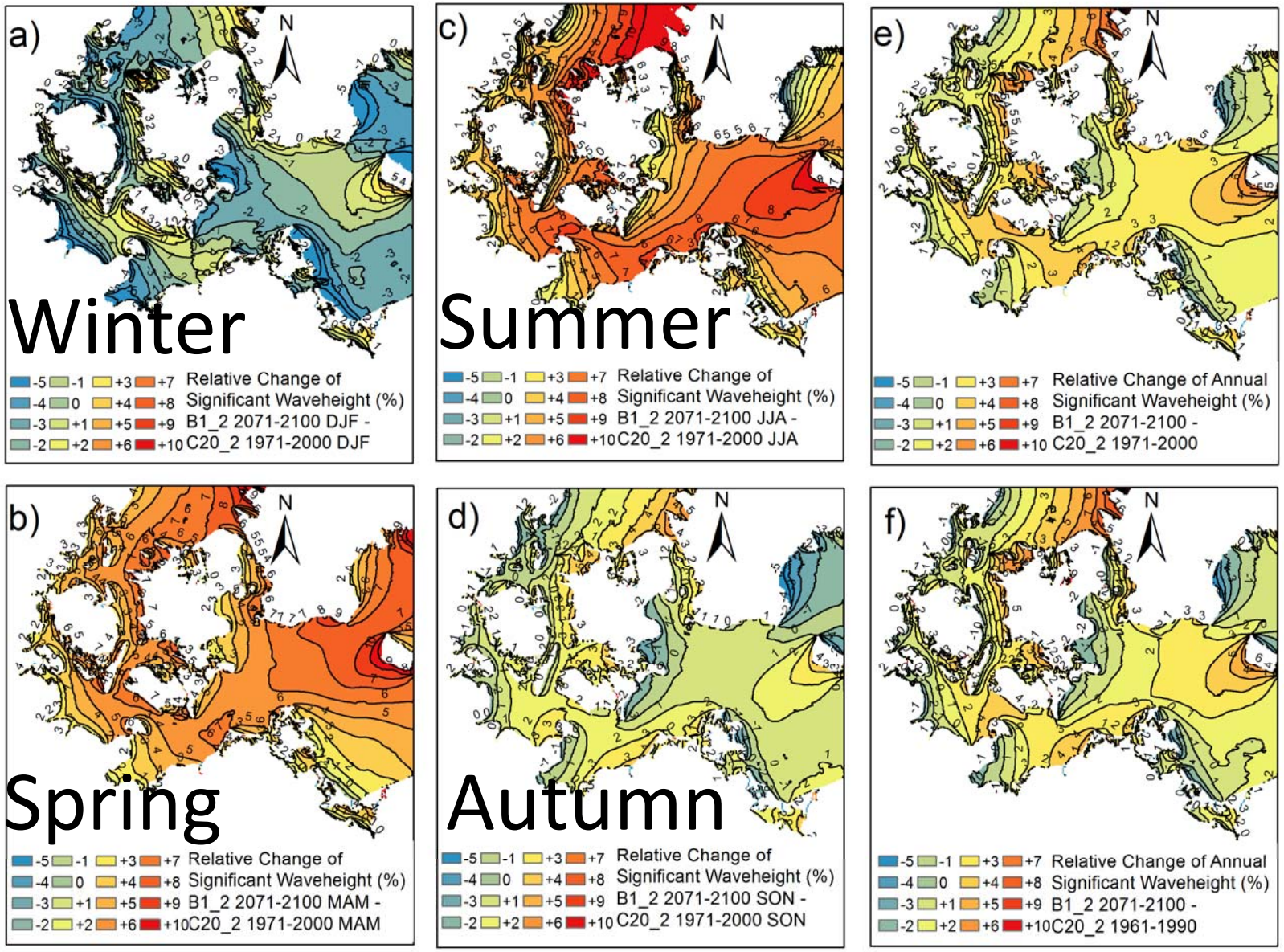
Bandwith of Changes:
-5.7% to +5.3%
(appr. 0.02m)

Lower and Higher values possible!

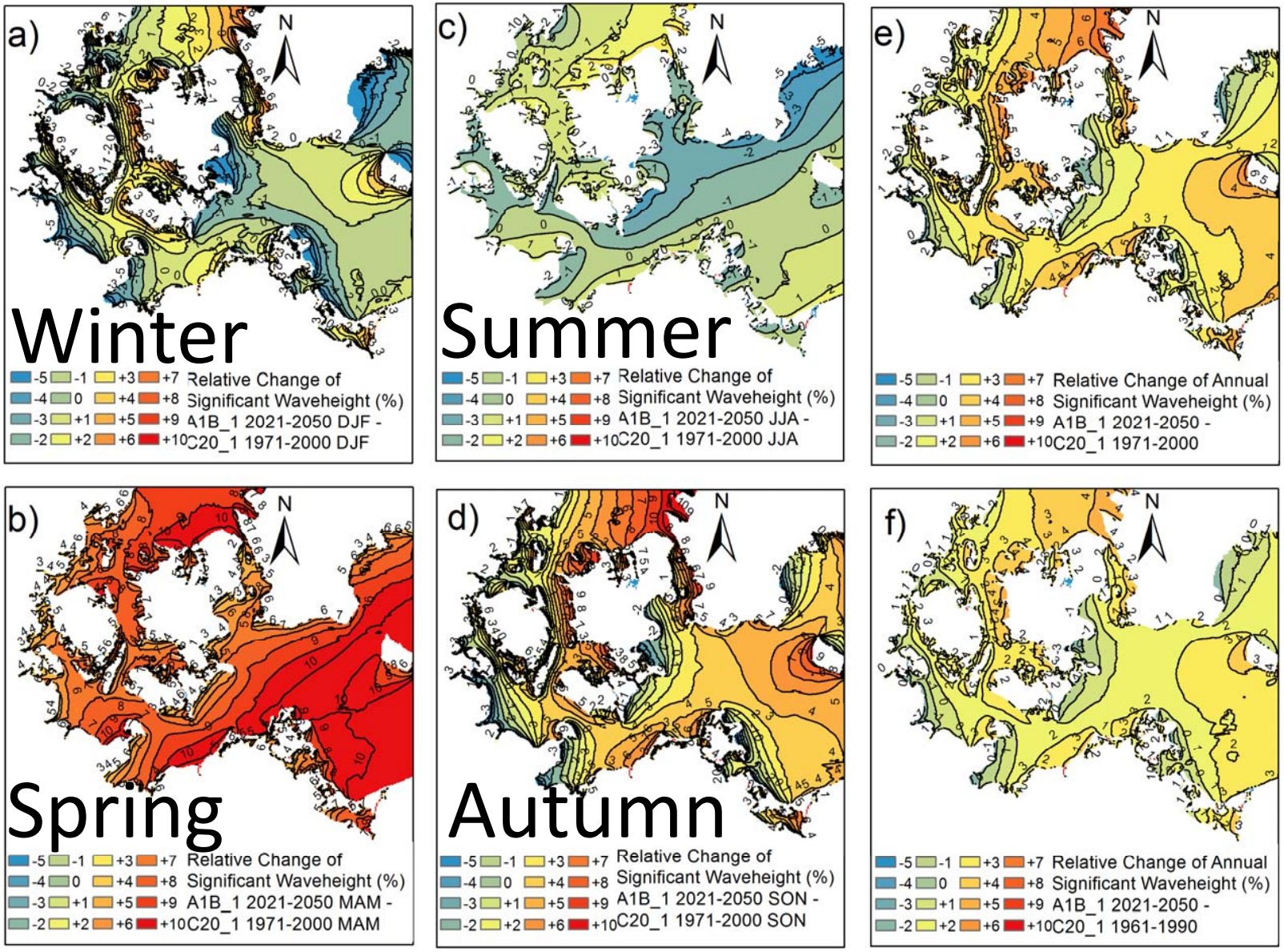
$\Delta\varnothing H_s$ Szenario 2100 A1B_2



$\Delta\varnothing H_s$ Szenario 2100 B1_2



$\Delta\varnothing H_s$ Szenario 2050 A1B_1



3. Results: 1) Changes of Average Wave Conditions – Wave Periods

Average Mean Wave Periods - Warnemünde						
Run	Period	∅ [s]	DJF [s]	MAM [s]	JJA [s]	SON [s]
C20_1	1971-2000	1.6290	1.6815	1.5262	1.6320	1.6778
C20_2	1971-2000	1.6377	1.6940	1.5472	1.6161	1.6951
A1B_1	2071-2100					
A1B_1	2021-2050					
A1B_2	2071-2100					
A1B_2	2021-2050					
B1_2	2071-2000					
B1_2	2021-2050					
B1_1	2071-2100					
B1_1	2021-2050					

Relative Changes of Mean Wave Periods - Warnemünde						
Run	Period	∅ [%]	DJF [%]	MAM [%]	JJA [%]	SON [%]
A1B_1	2071-2100	2.1	2.4	2.5	0.5	3.1
A1B_1	2021-2050	1.7	0.3	4.0	0.7	2.0
A1B_2	2071-2100	1.8	0.8	1.6	2.4	2.4
A1B_2	2021-2050	0.8	2.1	0.8	0.9	-0.7
B1_2	2071-2100	1.2	-0.9	1.9	2.8	0.9
B1_2	2021-2050	0.5	-1.3	1.4	1.6	0.4
B1_1	2071-2100					
B1_1	2021-2050					
Minimum	2100	1.2	-0.9	1.6	0.5	0.9
Maximum	2100	2.1	2.4	2.5	2.8	3.1
Minimum	2050	0.5	-1.3	0.8	0.7	-0.7
Maximum	2050	1.7	2.1	4.0	1.6	2.0
Minimum	2050,2100	0.5	-1.3	0.8	0.5	-0.7
Maximum	2050,2100	2.1	2.4	4.0	2.8	3.1

Bandwith of Changes:
-1.3% to +4.0%
(appr. 0.06s)

Slight Tendency towards higher values!

3. Results: 1) Changes of Average Wave Conditions – Wave Periods

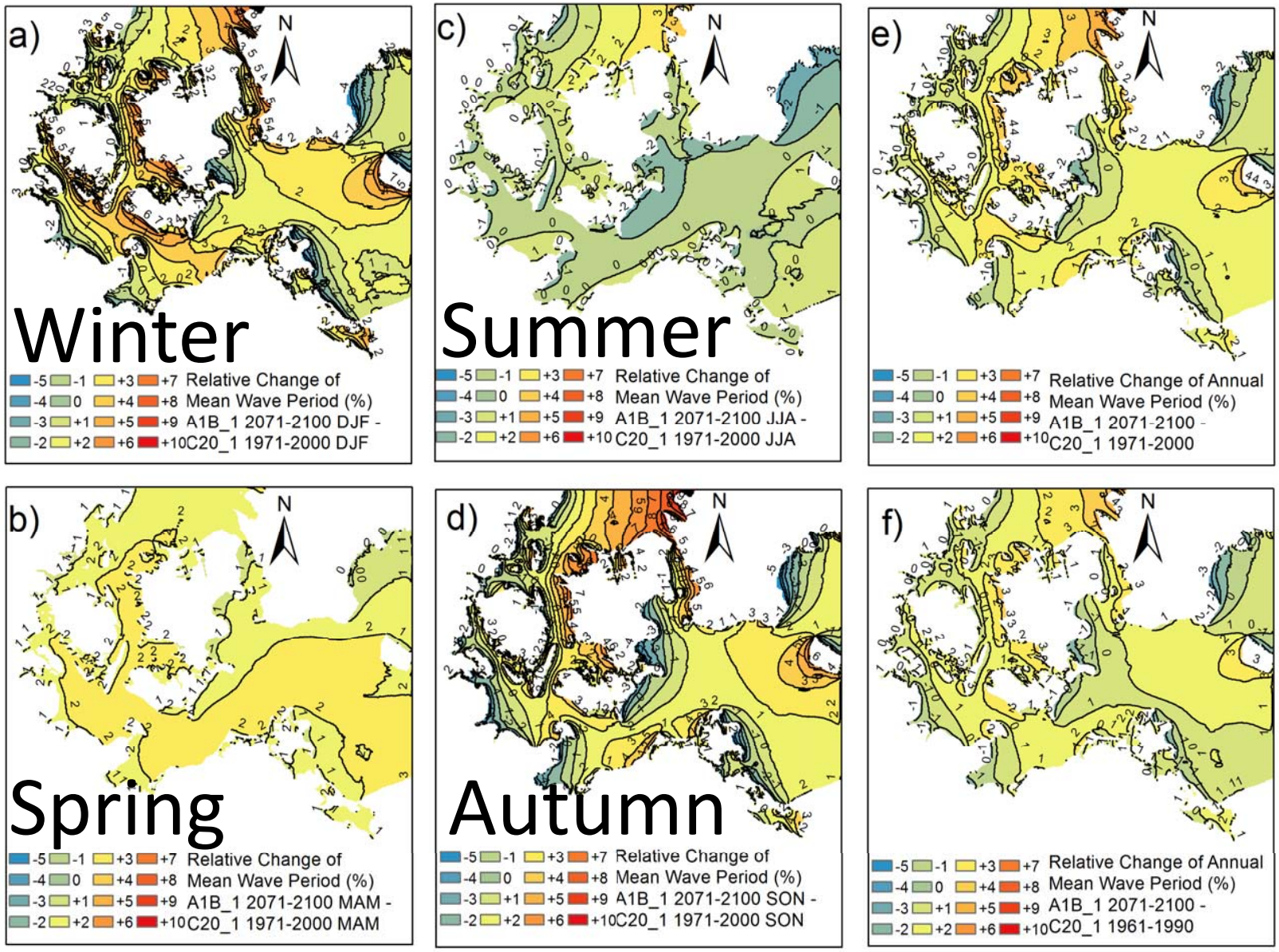
Average Mean Wave Periods – Travemünde						
Run	Period	∅ [s]	DJF [s]	MAM [s]	JJA [s]	SON [s]
C20_1	1971-2000	1.3615	1.4230	1.3731	1.2919	1.3593
C20_2	1971-2000	1.3664	1.4372	1.4005	1.2828	1.3464
A1B_1	2071-2100					
A1B_1	2021-2050					
A1B_2	2071-2100					
A1B_2	2021-2050					
B1_2	2071-2000					
B1_2	2021-2050					
B1_1	2071-2100					
B1_1	2021-2050					

Relative Changes of Mean Wave Periods - Travemünde						
Run	Period	∅ [%]	DJF [%]	MAM [%]	JJA [%]	SON [%]
A1B_1	2071-2100	-1.0	-2.1	1.2	-0.4	-2.6
A1B_1	2021-2050	-0.6	-2.4	1.9	0.0	-2.0
A1B_2	2071-2100	-1.1	-3.0	-0.8	0.4	-1.0
A1B_2	2021-2050	-0.6	-2.3	0.9	0.1	-1.2
B1_2	2071-2100	-0.9	-3.0	0.3	0.2	-0.8
B1_2	2021-2050	-0.3	-2.1	-0.2	1.3	0.1
B1_1	2071-2100					
B1_1	2021-2050					
Minimum	2100	-1.1	-3.0	-0.8	-0.4	-2.6
Maximum	2100	-0.9	-2.1	1.2	0.4	-0.8
Minimum	2050	-0.6	-2.4	-0.2	0.0	-2.0
Maximum	2050	-0.3	-2.1	1.9	1.3	0.1
Minimum	2050,2100	-1.1	-3.0	-0.8	-0.4	-2.6
Maximum	2050,2100	-0.3	-2.1	1.9	1.3	0.1

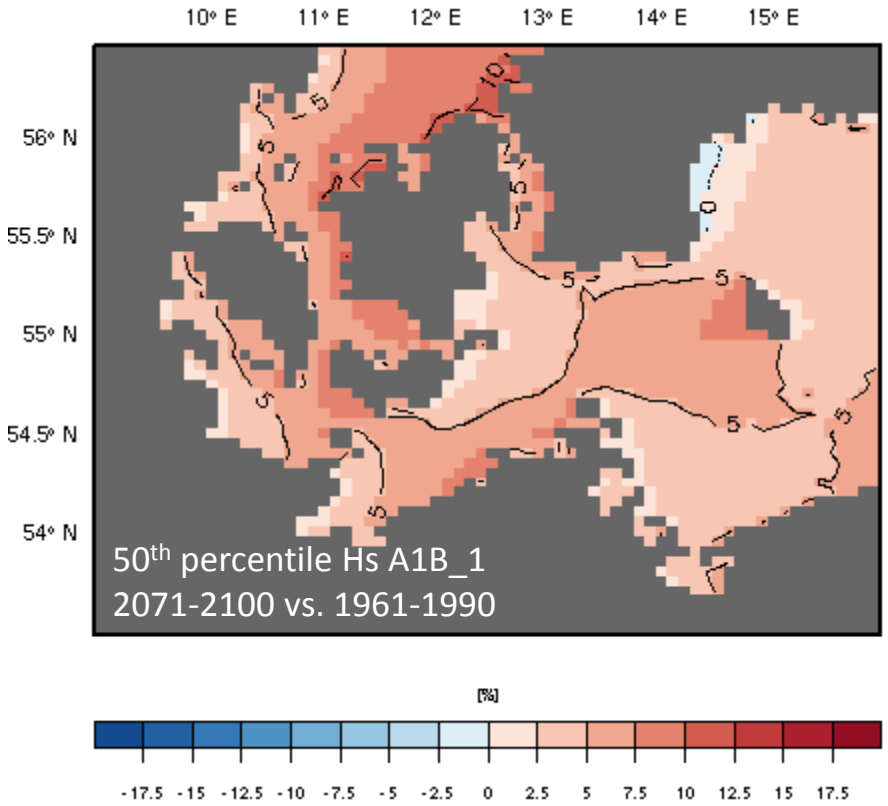
Bandwith of Changes:
-3% to +1.9%
(appr. 0.03s)

Lower and Higher values possible!

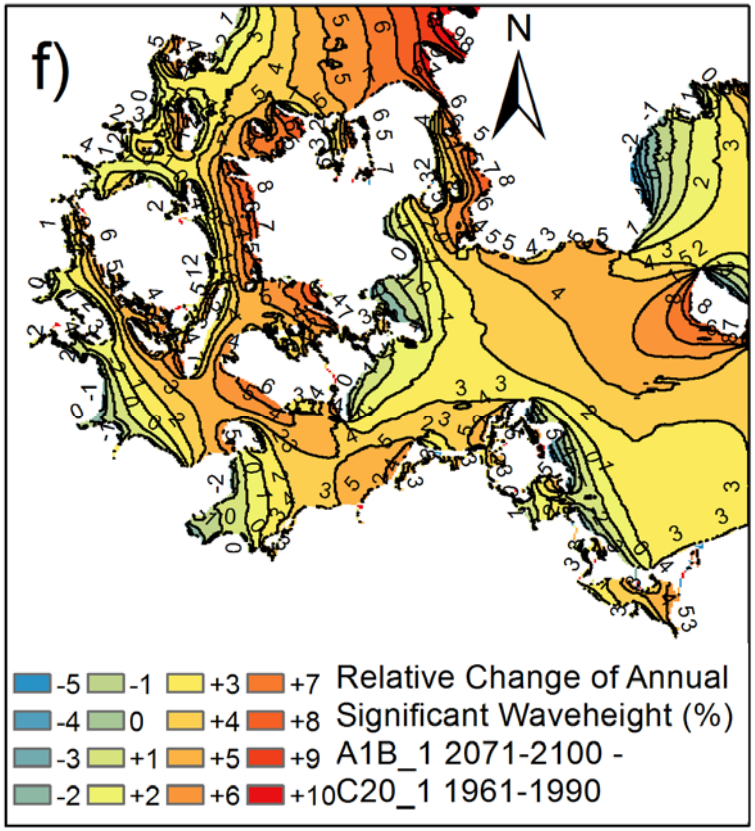
$\Delta\varnothing T_{m02}$ Szenario 2100 A1B_1



Comparison of Average Changes between SWAN<->WAM in the Western Baltic Sea



[Groll et al., 2013]



Comparison of Average Changes between different Methods (Hybrid-Approach)

	Change of average sign. wave height (min, max)			Change of average wave direction (min, max)		
Time period	2021-2050	2071-2100		2021-2050	2071-2100	
Warnemünde	+2% - +3%	+3% - +5%	+4% - +6%	+1° - +5°	+4° - +6°	
Travemünde	-2% - +1%	-1%	-2% - -1%	-1° - +5°	+1° - +2°	
Westermarkels-dorf (Fehmarn)	+2% - +5%	+4% - +7%		+0° - +4°	+3° - +5°	