National Oceanography Centre

Global Wave Height Trends and Variability from New Multimission Satellite Altimeter Products, Reanalyses, and Wave Buoys

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Outline

- The ESA Sea State CCI+ project & products
- Assessment of CCI+ Sea State v1.1 over the open ocean
  - Global climatologies, seasonal variations, comparisons with other sea state products
  - Comparisons with *in situ* data and other sea state products
  - Long-term trends in altimeter Hs
- Considerations for analysis in the coastal zone (future work)
- Summary and Conclusions
- **Results now published in GRL at http://dx.doi.org/10.1029/2019GL086880**

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RESEARCH LETTER
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Key Points:
- New multi-mission altimeter products show regional differences in wave height climatologies and trends

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Multimission Satellite Altimeter Products,
Reanalyses, and Wave Buoys

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The ESA Sea State CCI+ project

- Funded by the European Space Agency Climate Change Initiative+
- 36 months project
  - Lead: Fabrice Ardhuin (Ifremer) / Ellis Ash (SatOC Ltd)
  - Large international team
  - KO: June 2018

- Objectives
  - To produce climate-quality satellite products for Essential Climate Variables (ECV) for Sea State
    - Focus on ensuring long-term consistent multi-mission products, not Cal/Val of individual missions
  - Case studies include trends, extremes, polar & coastal
    - Including, ultimately, trends in extremes at the coast!

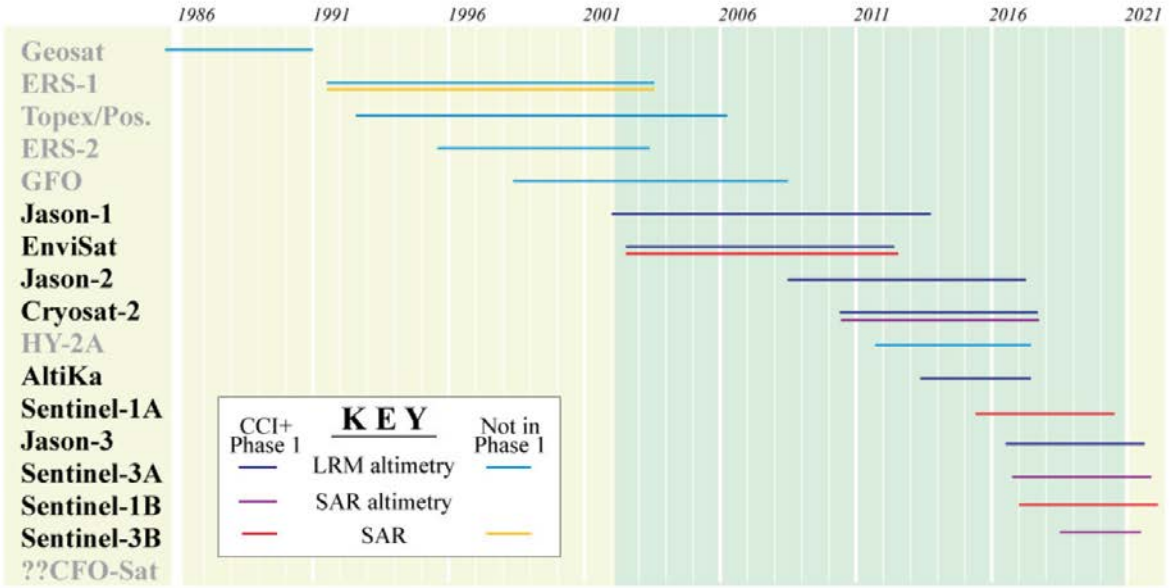
Sea State ECV requirements

- ECV defined by WMO Global Climate Observing System (GCOS)
- GCOS formal requirement for Sea State

Product	Frequency	Resolution	Required uncertainty	Required Stability (per decade)
Hs	3-hourly	25 km	10 cm	5 cm

CCI+ Sea State products

- CCI+ Sea State ECVs
  - Altimeter: Hs and Sigma0 (mean square slope)
  - Imaging SAR: Hs, period, direction, 2D spectra
  - 1992-2018
- Strong heritage from GlobWave



- CCI+ Sea State Version 1 products available since July 2019
  - Altimeter Hs only, all missions since 1991 (ERS-1 onwards)
  - https://forms.ifremer.fr/lops-siam/access-to-esa-cci-sea-state-data/
    - Level 2P: along-track products separated per mission and pass (7km)
    - Level 3: edited multi-mission daily products
    - Level 4: multi-mission monthly gridded 1° resolution

sea state cci

CCI+ Sea State v1 altimeter product assessment

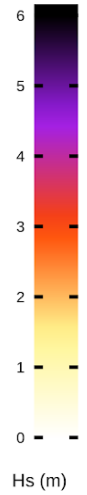
Datasets

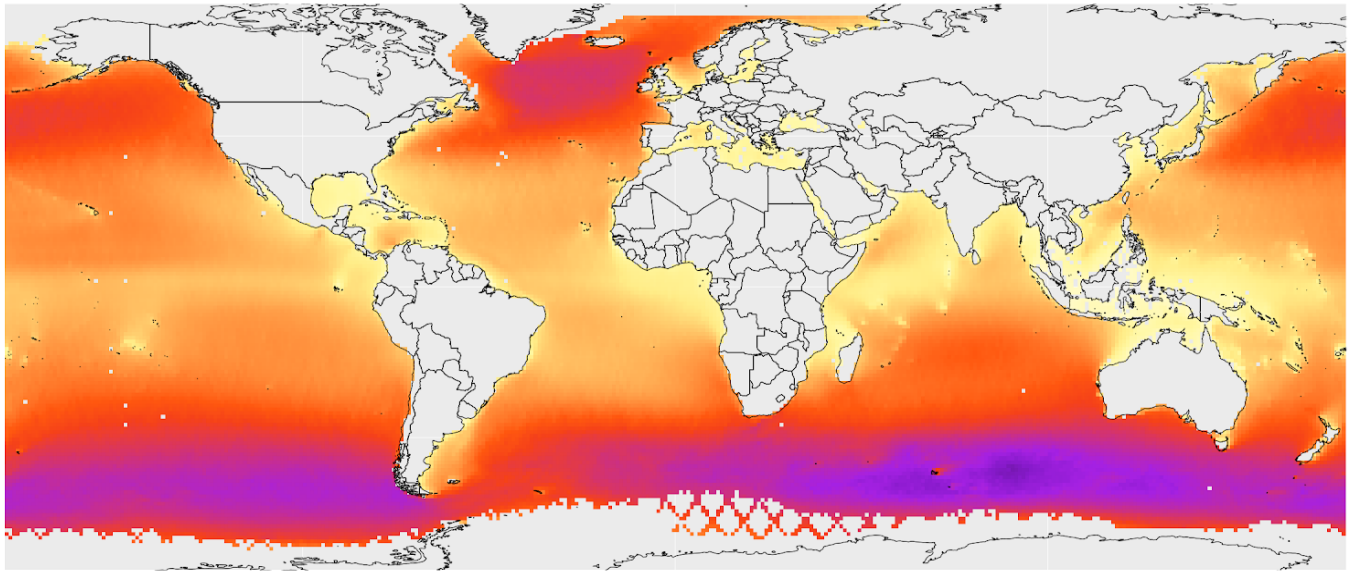
Altimetry-based	Model-based
CCI+ Sea State v1.1 Level 4 altimeter Hs	ERA5 reanalysis
Ribal & Young, 2019: multi-mission altimeter (Hs, U10)	ERA5-hindcast (courtesy Jean Bidlot) – no assimilation

Altimeter Hs climatology

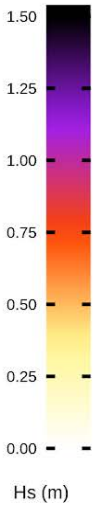
- 1992-2018, 1 deg

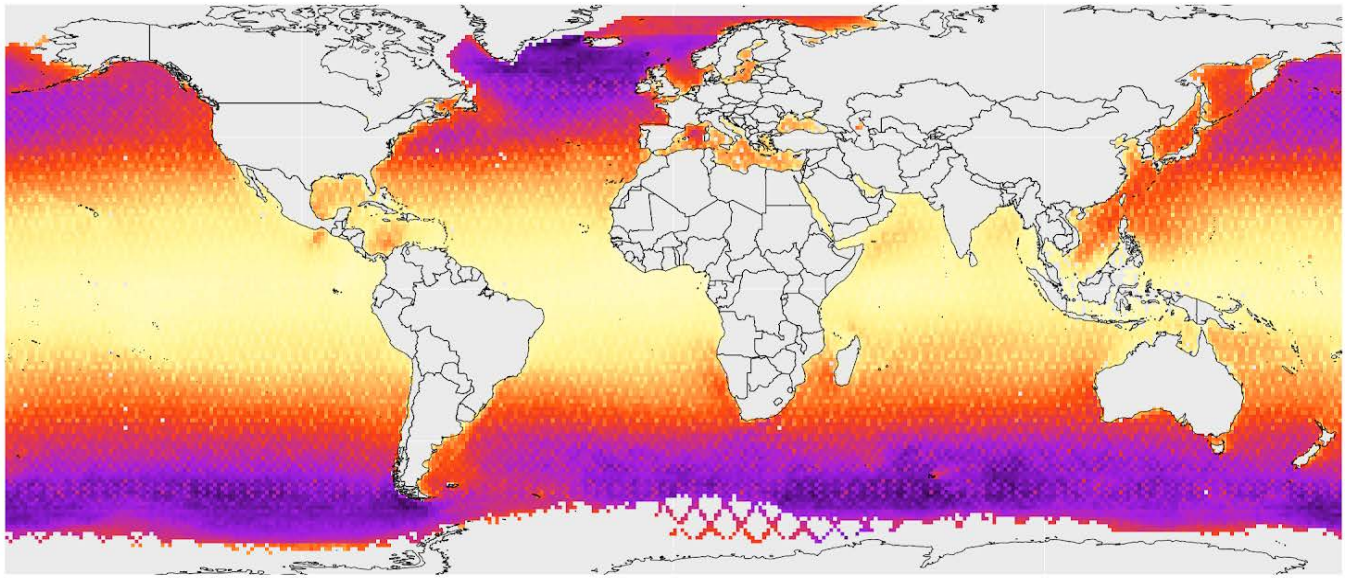
Mean Hs





Mean RMS

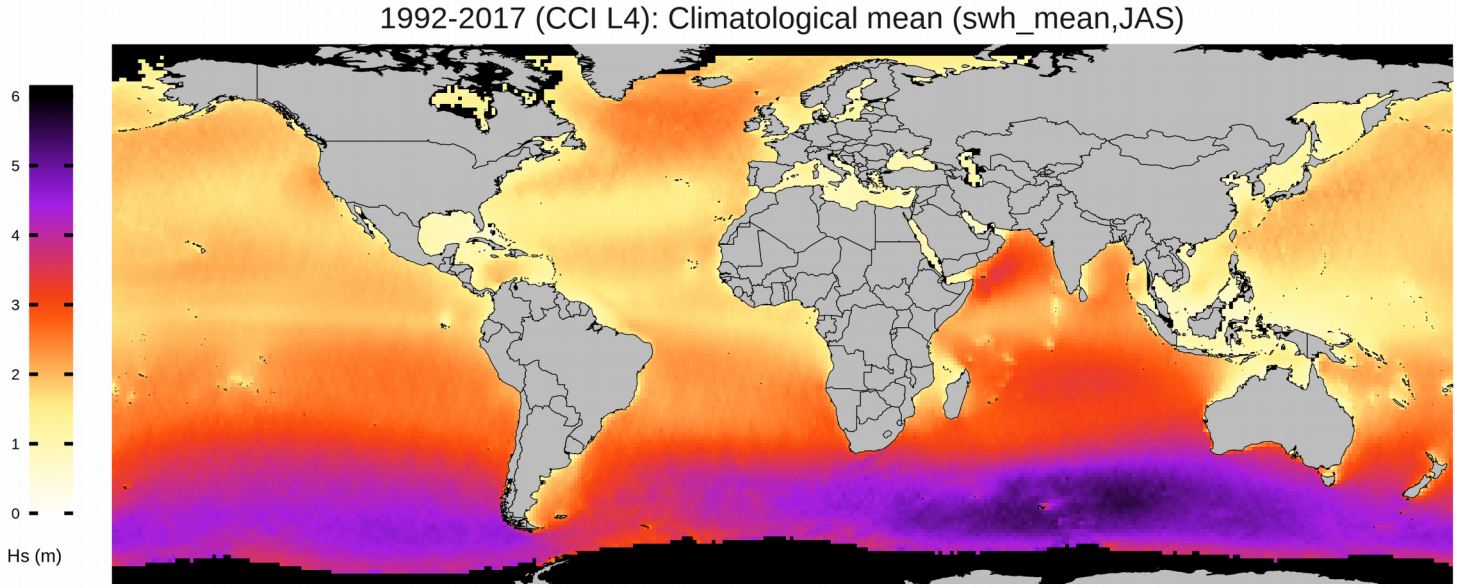




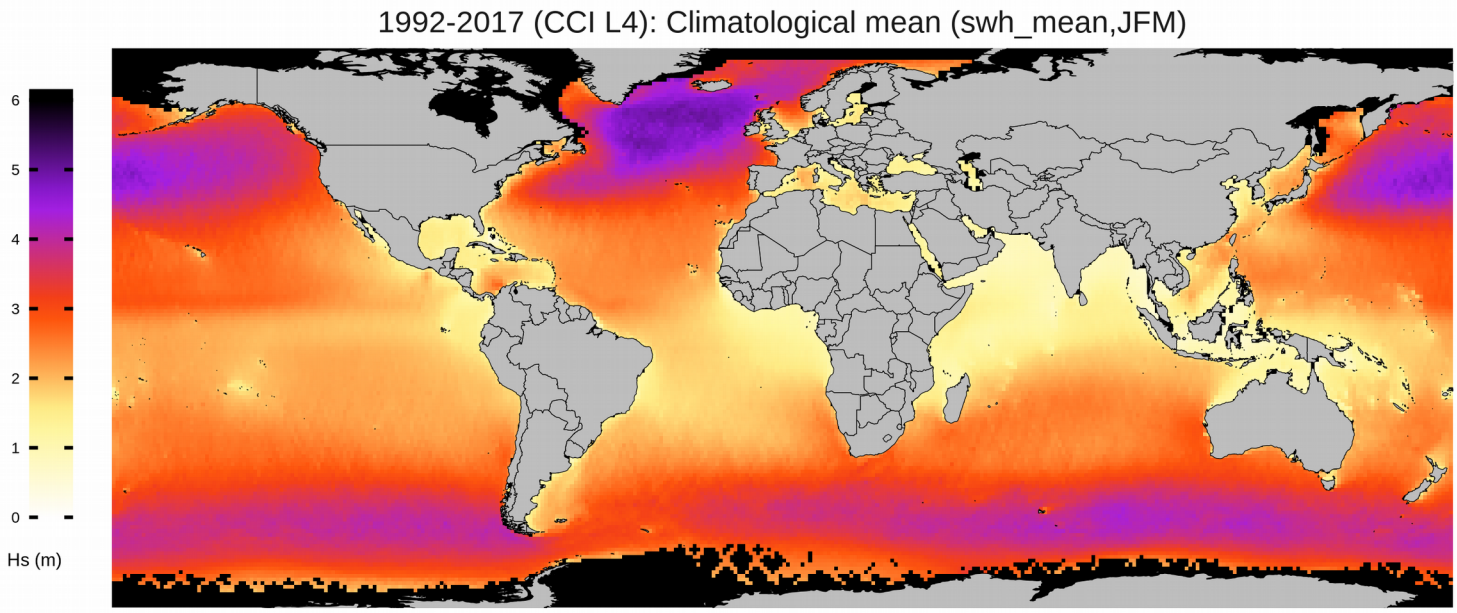
Seasonal variability

- 1992-2017, 1 deg

SH Winter
Jul-Sept

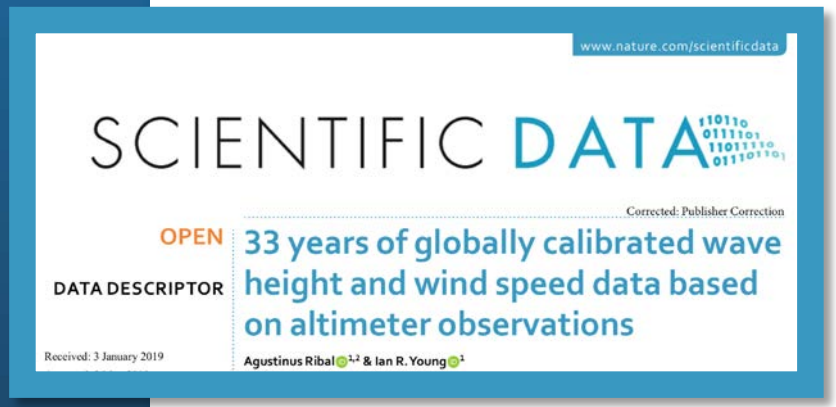


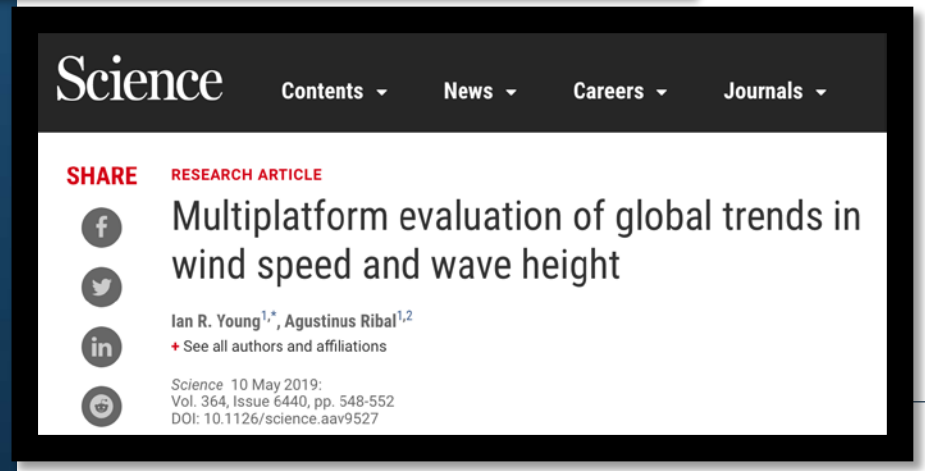
SH Summer
Jan-March

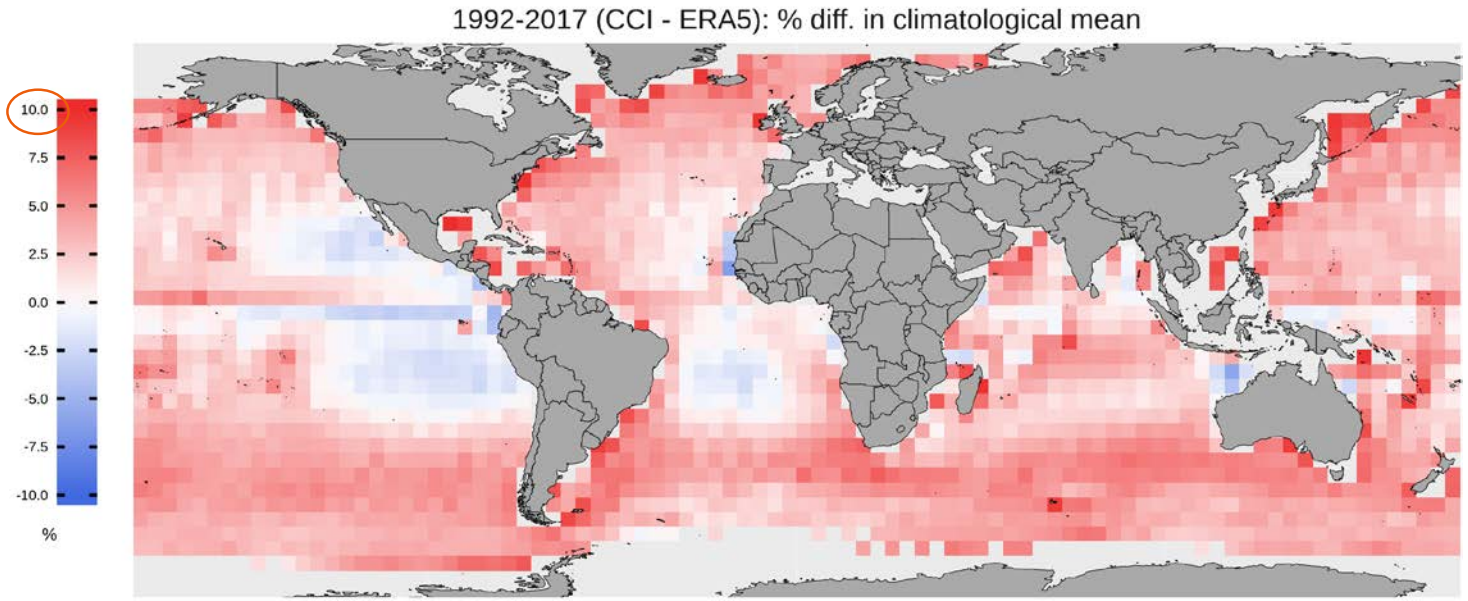


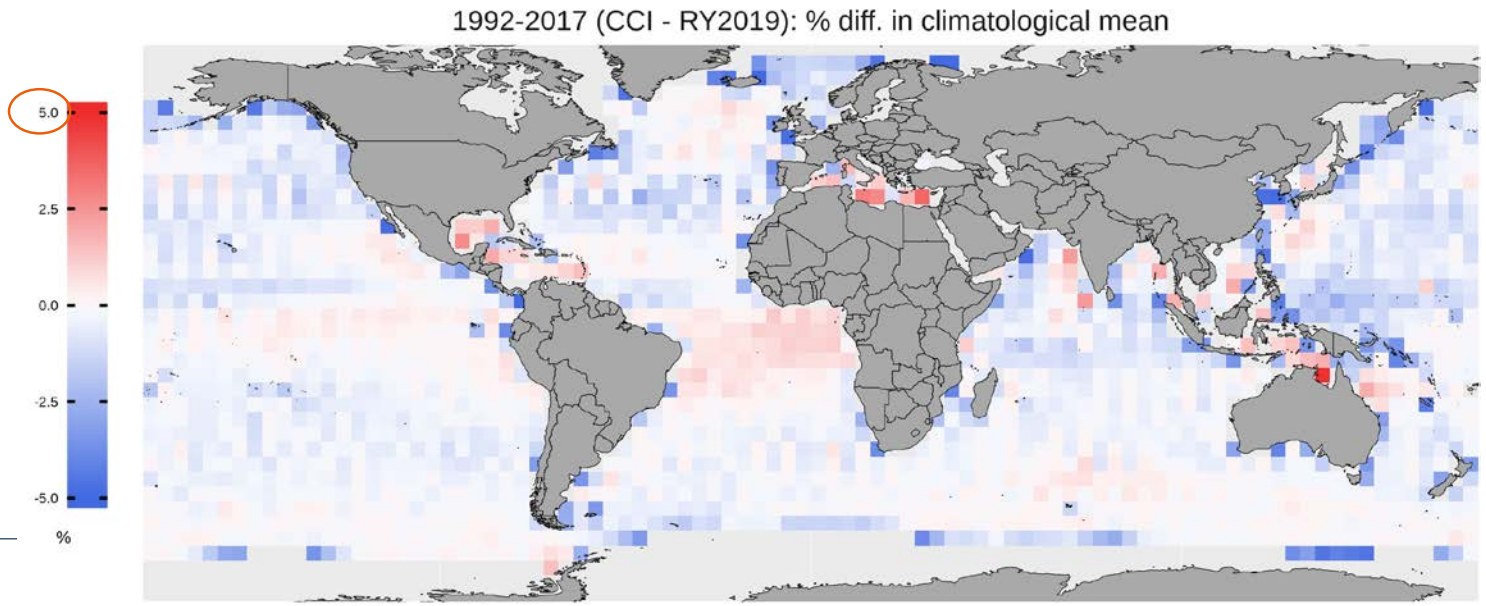
Comparisons with other sea state products

- 1992-2017, 4 deg
- % difference in **annual** climatological mean:
  CCI - ERA5 (top panel)
  CCI - RY2019 (bottom panel)





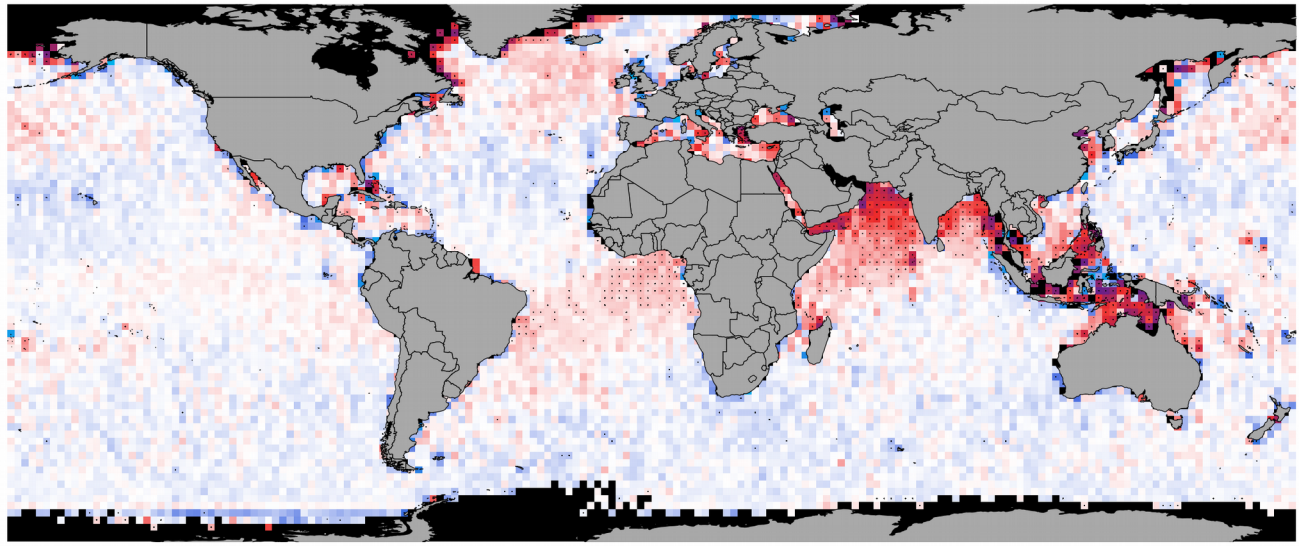




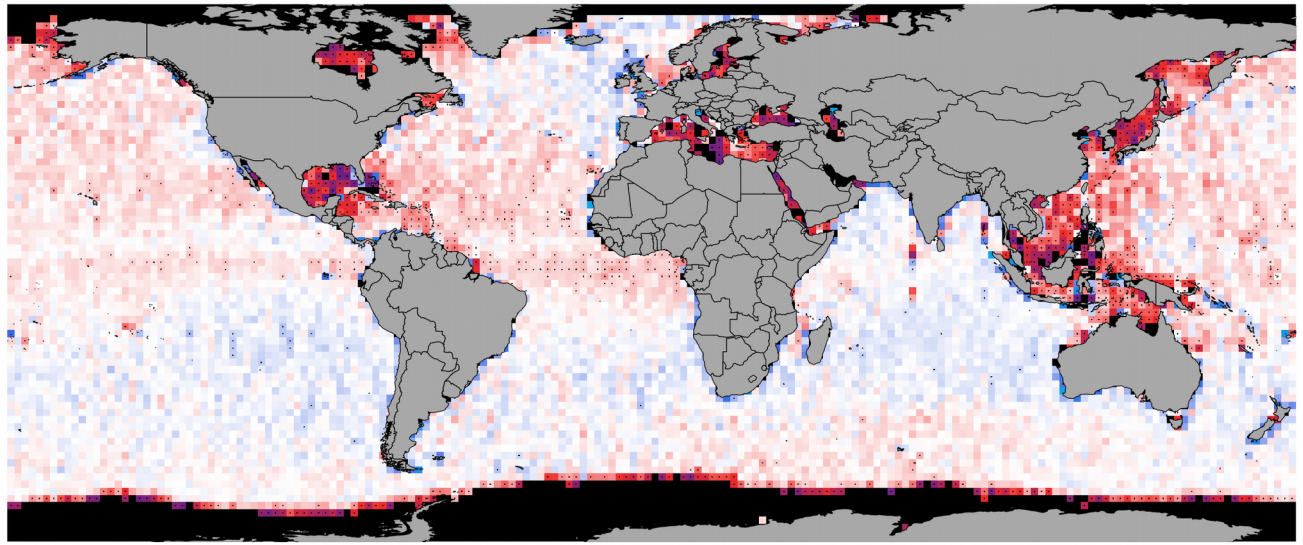
Robustness of difference in climatological mean

- % difference in **seasonal** climatological mean for CCI and RY2019.
- 1992-2017, 2 deg, JFM (panel A)
  JAS (panel B)
- Statistical significance at 10% marked by dots (via bootstrap of monthly data)
- Cautious interpretation of robustness advised owing to possible systematic errors that remain poorly understood, e.g. stability, continuity and coverage of *in situ* observations from buoys used for calibration.
- Figure S2 (Supporting Information) from *Timmermans et al. (2020)*.

(A) 1992-2017[JFM] (CCI2019 - RY2019): % diff. in climatological mean

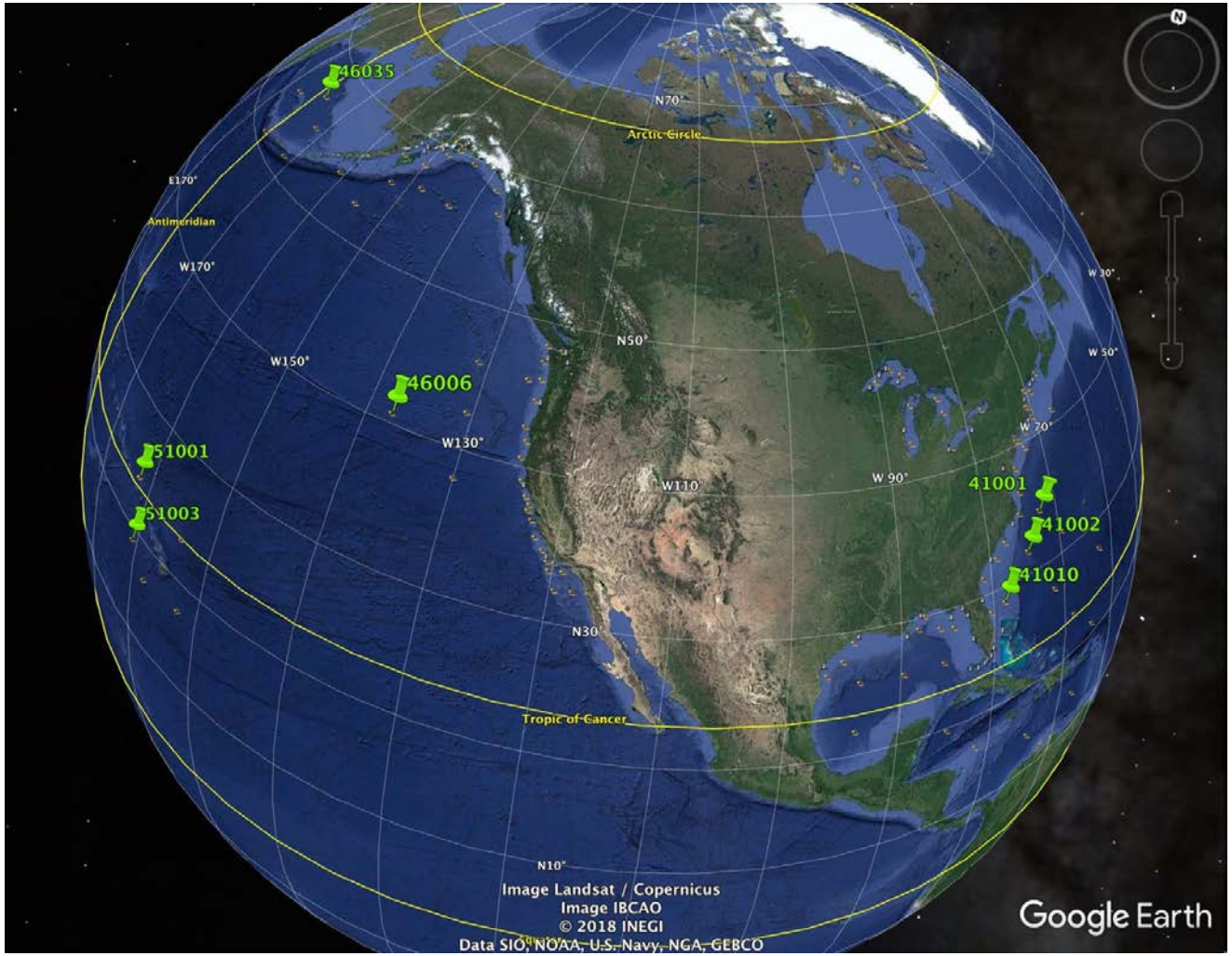


(B) 1992-2017[JAS] (CCI2019 - RY2019): % diff. in climatological mean



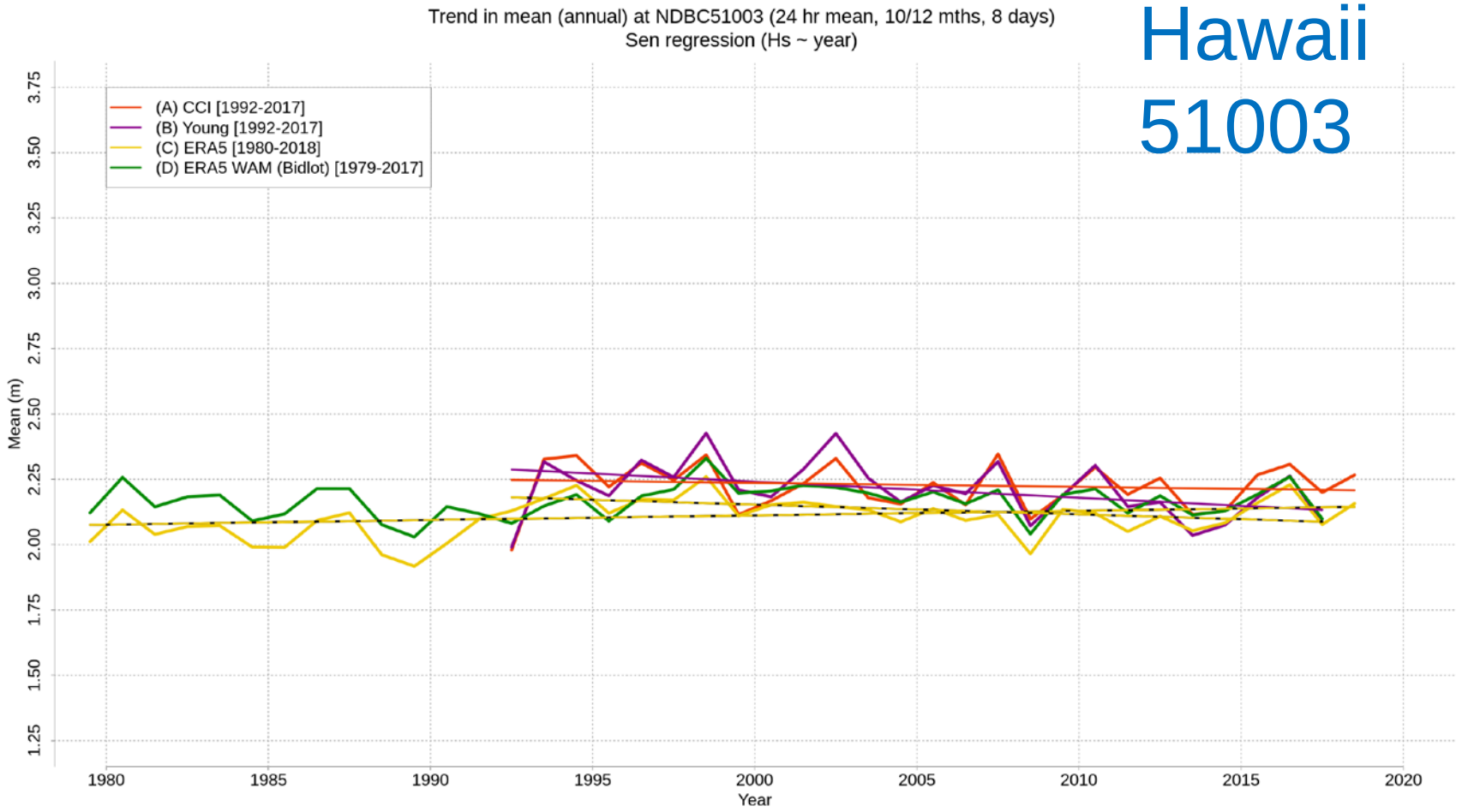
Comparison with in situ data and other sea state products

- Hs time series at selected buoys
  - NDBC
  - long-term buoy deployments
  - various wave climates
- Inter-comparisons with altimeter, in situ and model products
- 51003 (Hawaii)
- 41002 (W Atlantic)
- 46006 (E Pacific)



Comparison with in situ data and other sea state products

- CCI and RY19 show similar variability, occasional biases (± 0.1 m) & negative trends
  - Stronger negative Hs trend in RY2019
- ERA5 and ERA5-h both biased low, with weaker interannual variability
- Note differences in estimated trends for different time periods
  - Trend is opposite over longer period



Hawaii 51003

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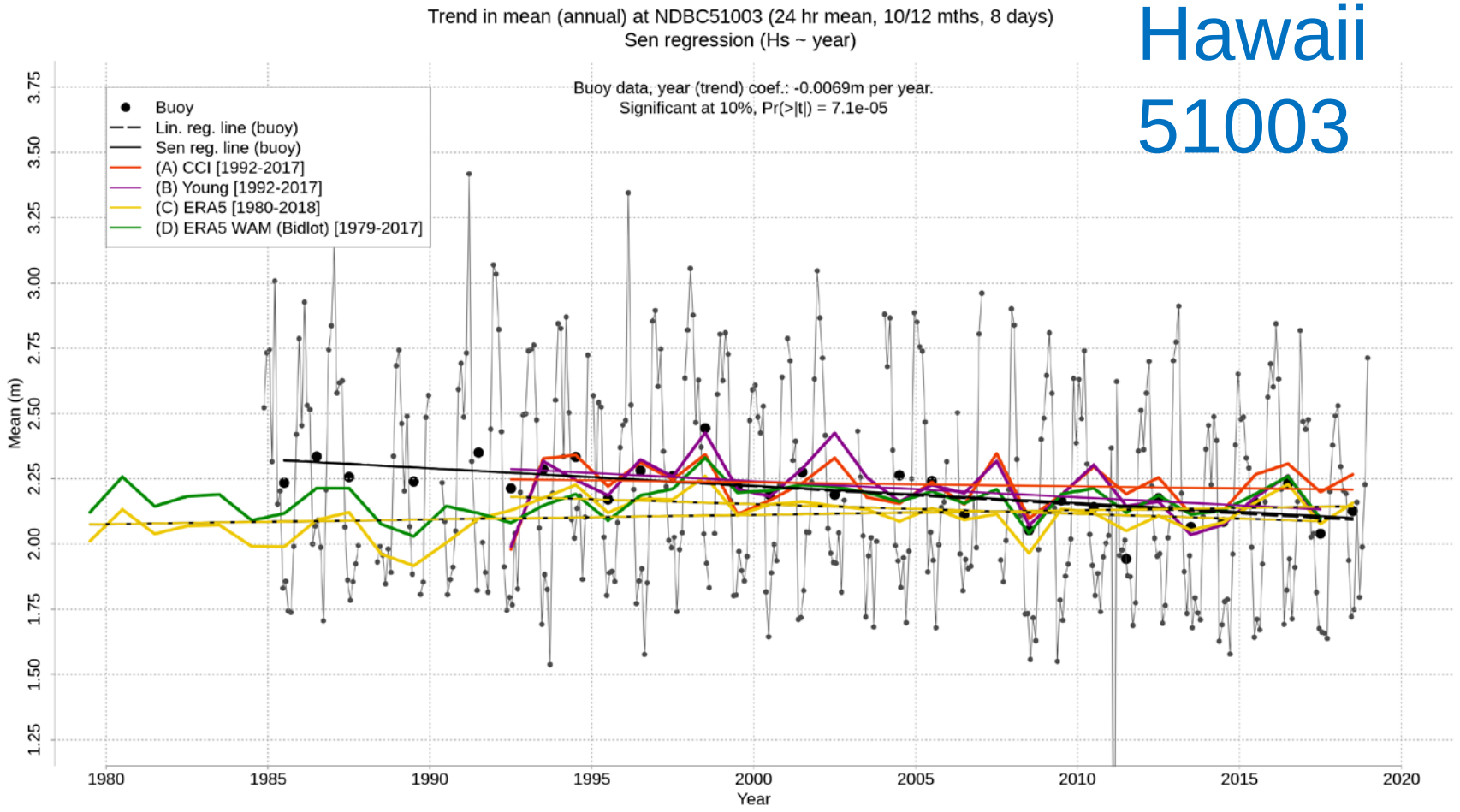
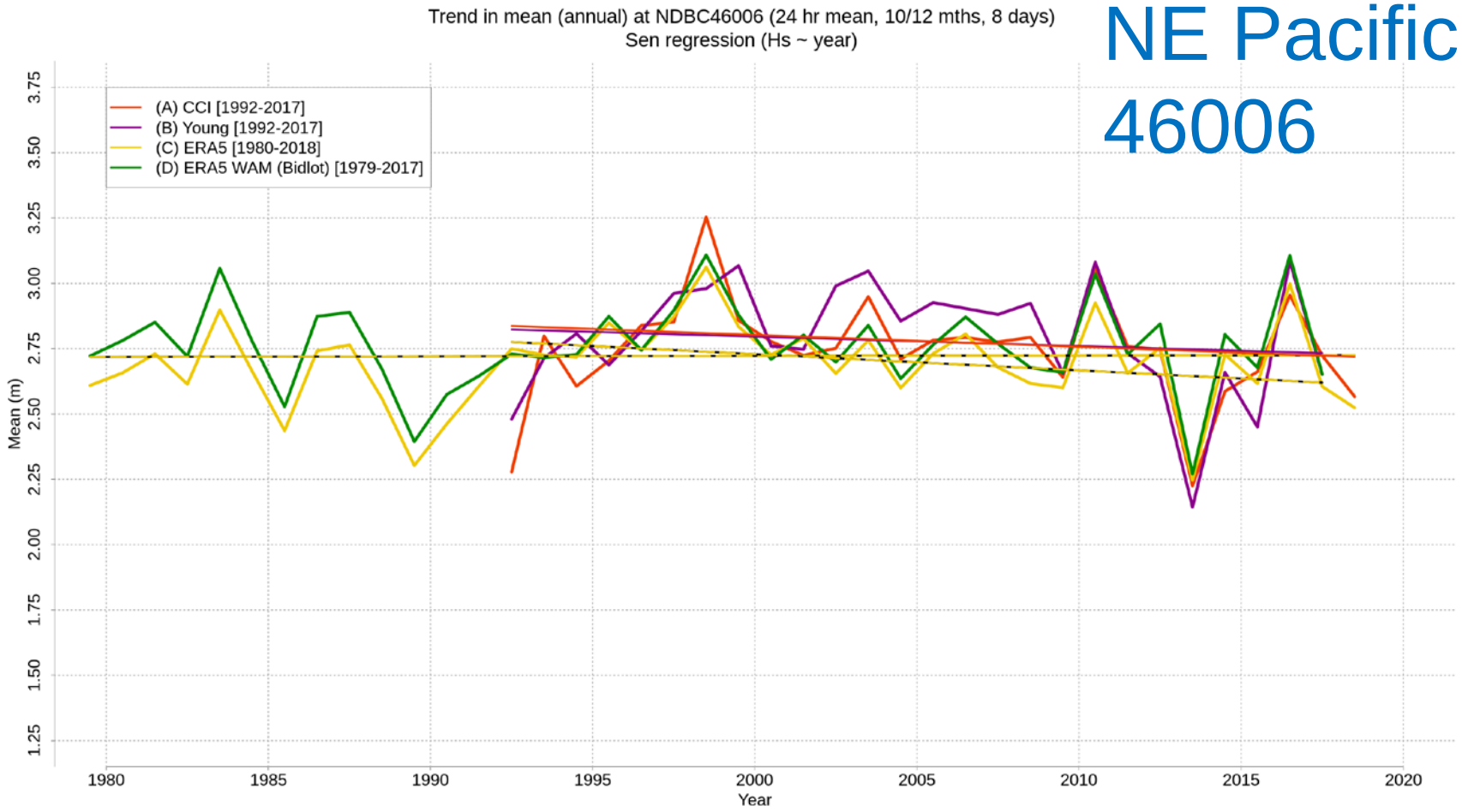


Hawaii 51003

Buoy data from 1985, confirm stronger negative trend seen in RY2019

Comparison with in situ data and other sea state products

- Better agreement between all products, particularly towards end of altimeter era
- Trends are broadly consistent between satellite and model products

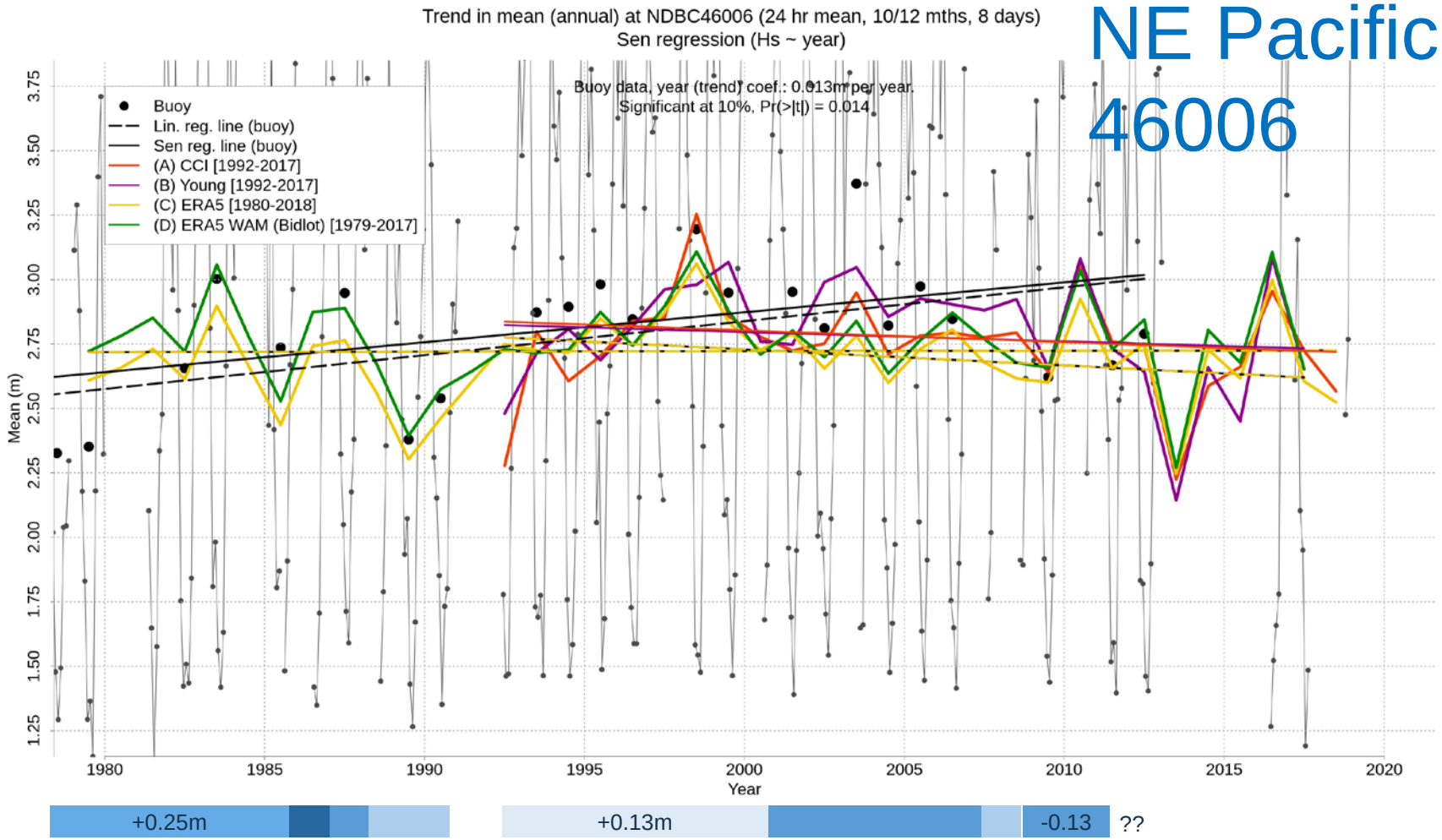


NE Pacific 46006

BUOY data at this site

Comparison with in situ data and other sea state products

- Better agreement between all products, particularly towards end of altimeter era
- Trends are broadly consistent between satellite and model products
- Large variability in buoy Hs on seasonal to decadal scales
- Buoy Hs shows opposite (positive) trend!
- But, strong concerns about long-term stability of the BUOY data at this site



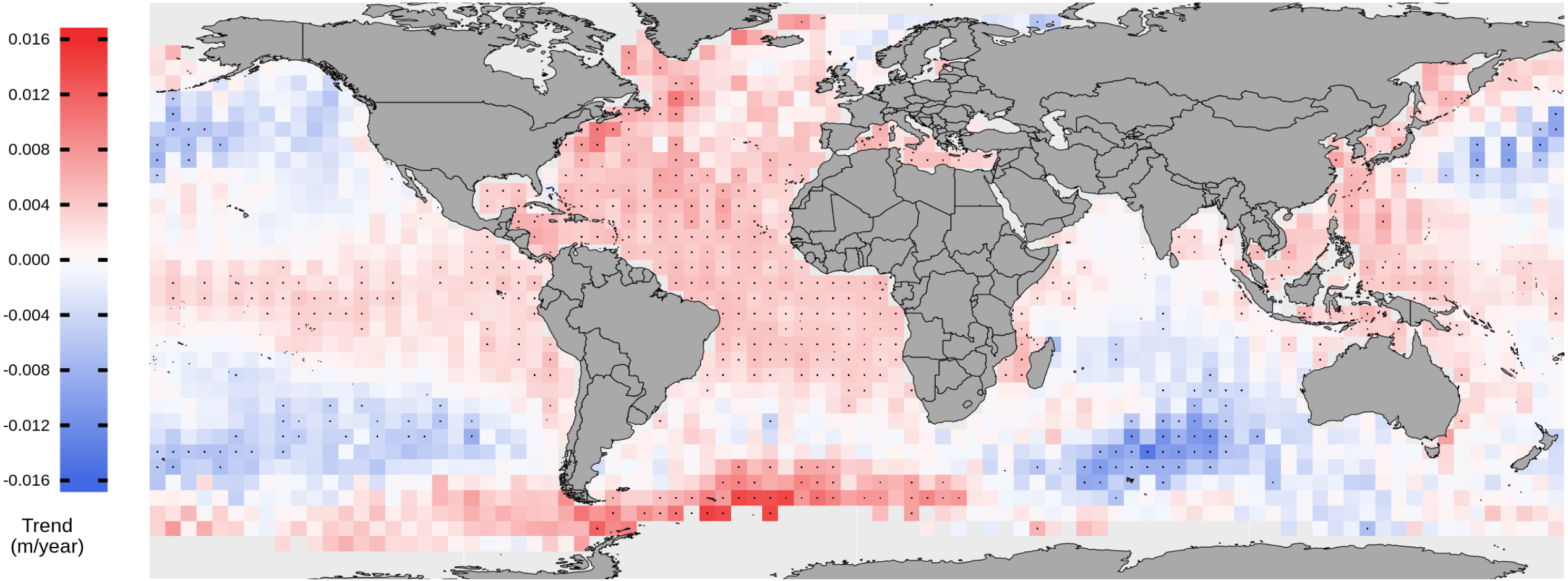
NE Pacific 46006

Impact of changes in buoy platform/sensor (Gemmrich et al., 2011)

Long-term trends in Hs

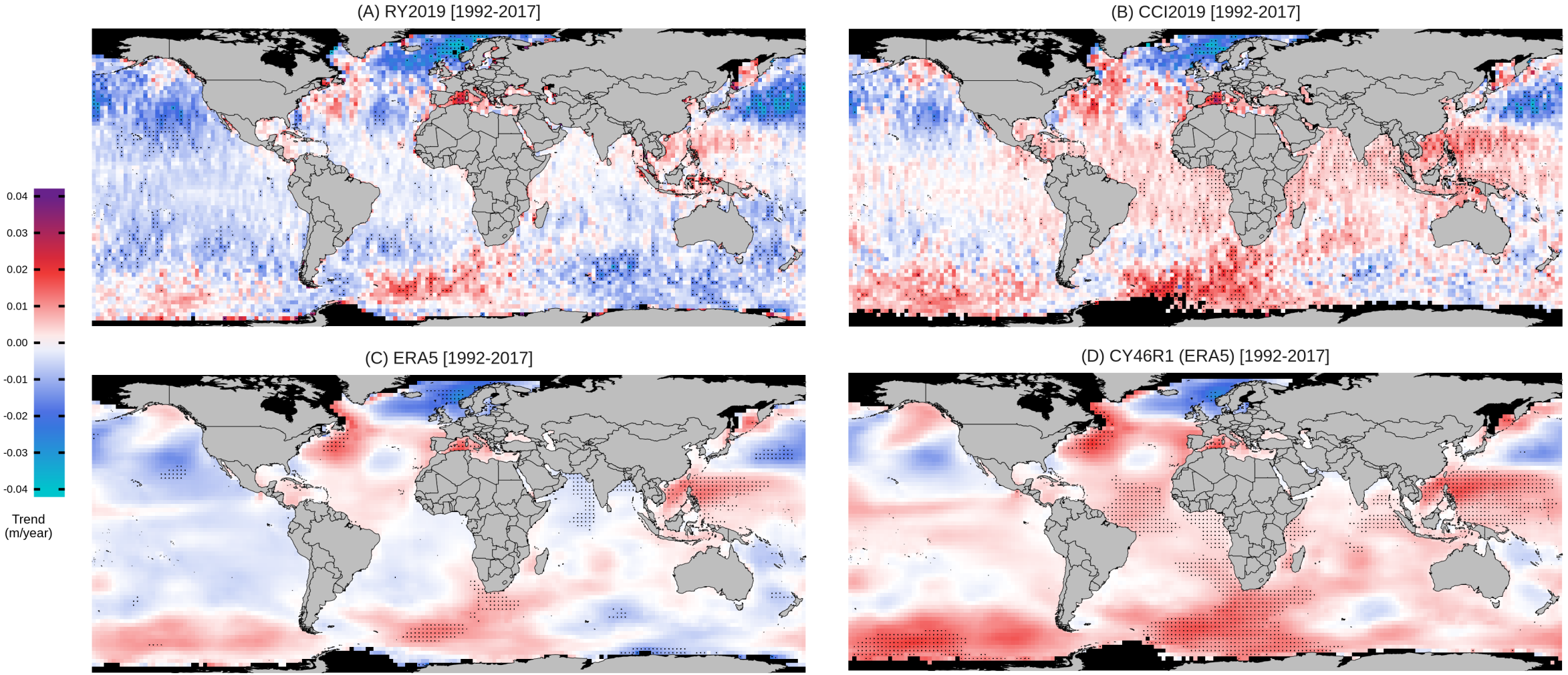
CCI+ Sea State: altimeter Hs trends (4 deg grid)

1992-2018 (CCI L4) Mean trend in annual Hs (from linear regression model)



Strong geographical patterns in CCI Hs trend. Grid cells with dots denote 5% trend significance.

Hs trends in different sea state products (JFM)



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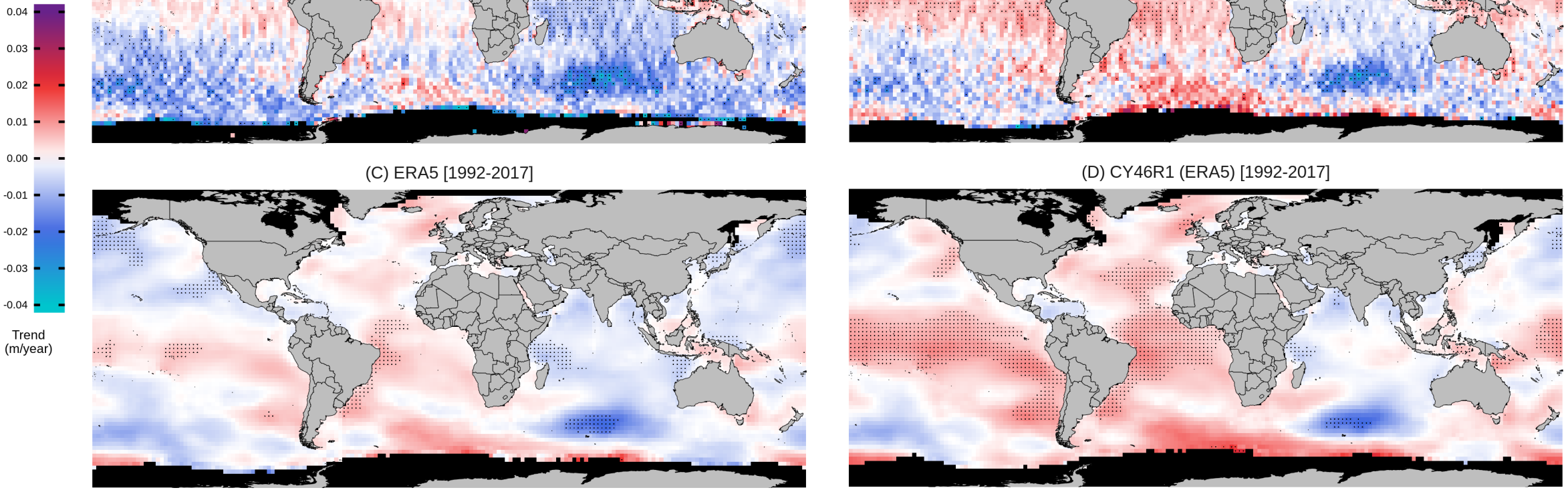
Hs trends in different sea state products (JAS)

(A) RY2019 [1992-2017]

(B) CCI2019 [1992-2017]



(C) ERA5 [1992-2017]

(D) CY46R1 (ERA5) [1992-2017]

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Assessment in the coastal zone
Outlook & Challenges

- Outlook
  - Extremes; coastal sea state; trends at the coast trends in extremes at the coast
- Challenges
  - Data availability in the coastal zone
    - use dedicated coastal retrackers to minimize data loss at the coast
  - Calibration issues
    - Low sea states in coastal regions
  - Small scale ocean decorrelation
    - retain high-resolution information i.e. no/careful smoothing
  - How to aggregate altimeter data according to sea state scales of variability ?
  - Temporal sampling of extreme events with altimetry ??
  - Validation
    - More in situ networks, but not designed to address climate change problems
  - Etc...

Summary & Conclusions

- ESA CCI+ Sea State project has produced a new multi-mission satellite altimeter products for Hs
- Assessment of CCI Sea State Level 4 gridded products (1992-2018) shows good consistency of Hs climatological fields with Ribal & Young (2019)
  - But ERA5 biased low v CCI Hs
- Inter-comparisons at buoy sites show:
  - Models biased low with weak variability, and sometimes show opposite trends over long/short periods
  - Buoy Hs time series confirm trends in turn for CCI and Ribal & Young (2019)
    - reliability of buoy Hs for climate applications ?
- Global maps of CCI Hs trends show strong spatially coherent patterns
  - E.g. strong positive trends in Atlantic and Southern Ocean, negative trends in Indian Ocean
- Hs trends is different products show similar spatial fingerprints but different magnitudes
  - Ribal & Young (2019) show more strongly negative trends; Reanalyses/hindcasts trends more strongly positive
  - Raises questions about uncertainties and impact of altimeter Hs calibration methodology
- Work just beginning on extreme and coastal sea states
  - Where issues are even more challenging than in the open ocean
- **Key results now in GRL at http://dx.doi.org/10.1029/2019GL086880**