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Elizabeth Kent

Role of SST forcing in reanalysis and ability to reconstruct climate records

Focus on in situ and long-term observations

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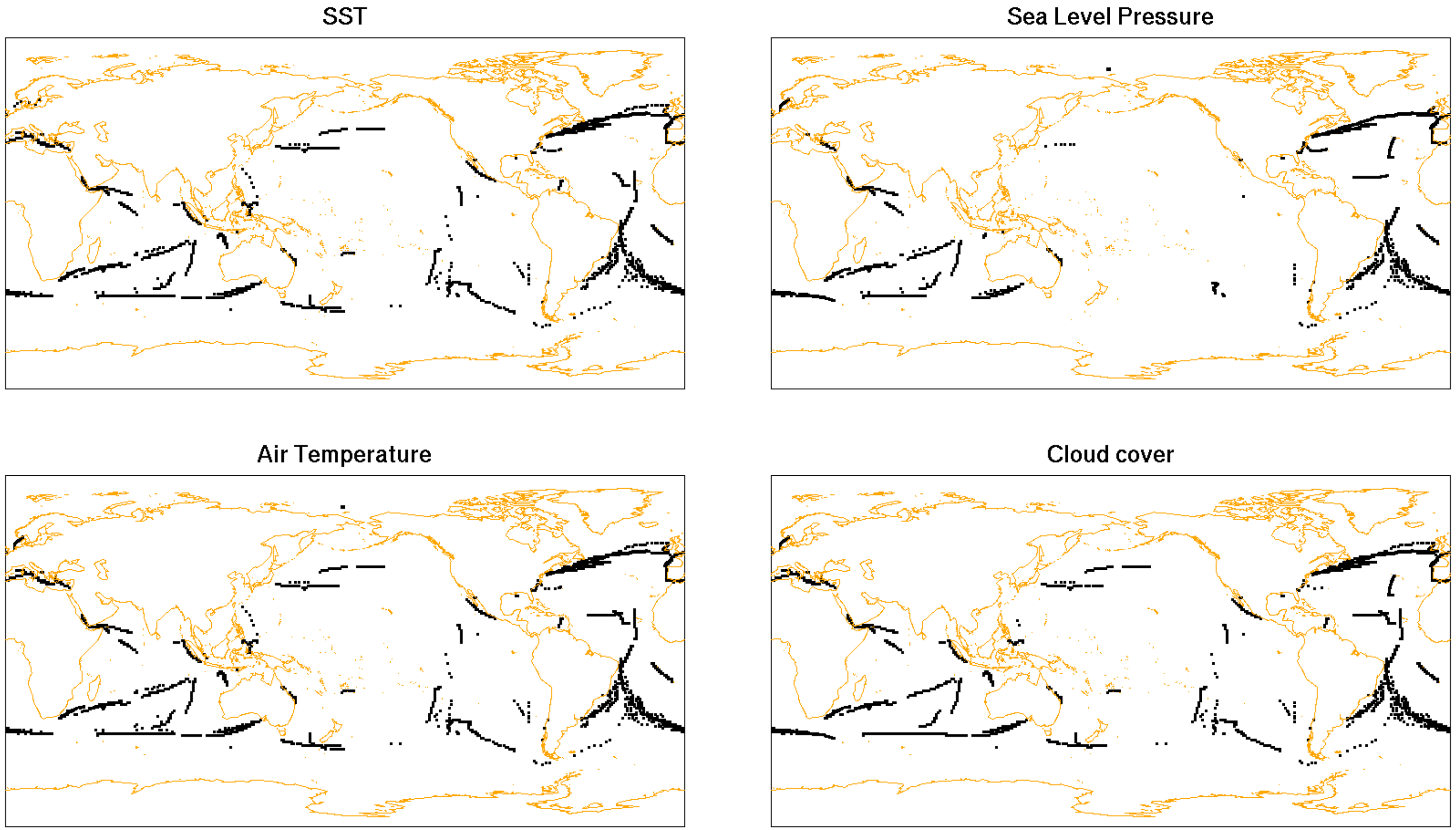
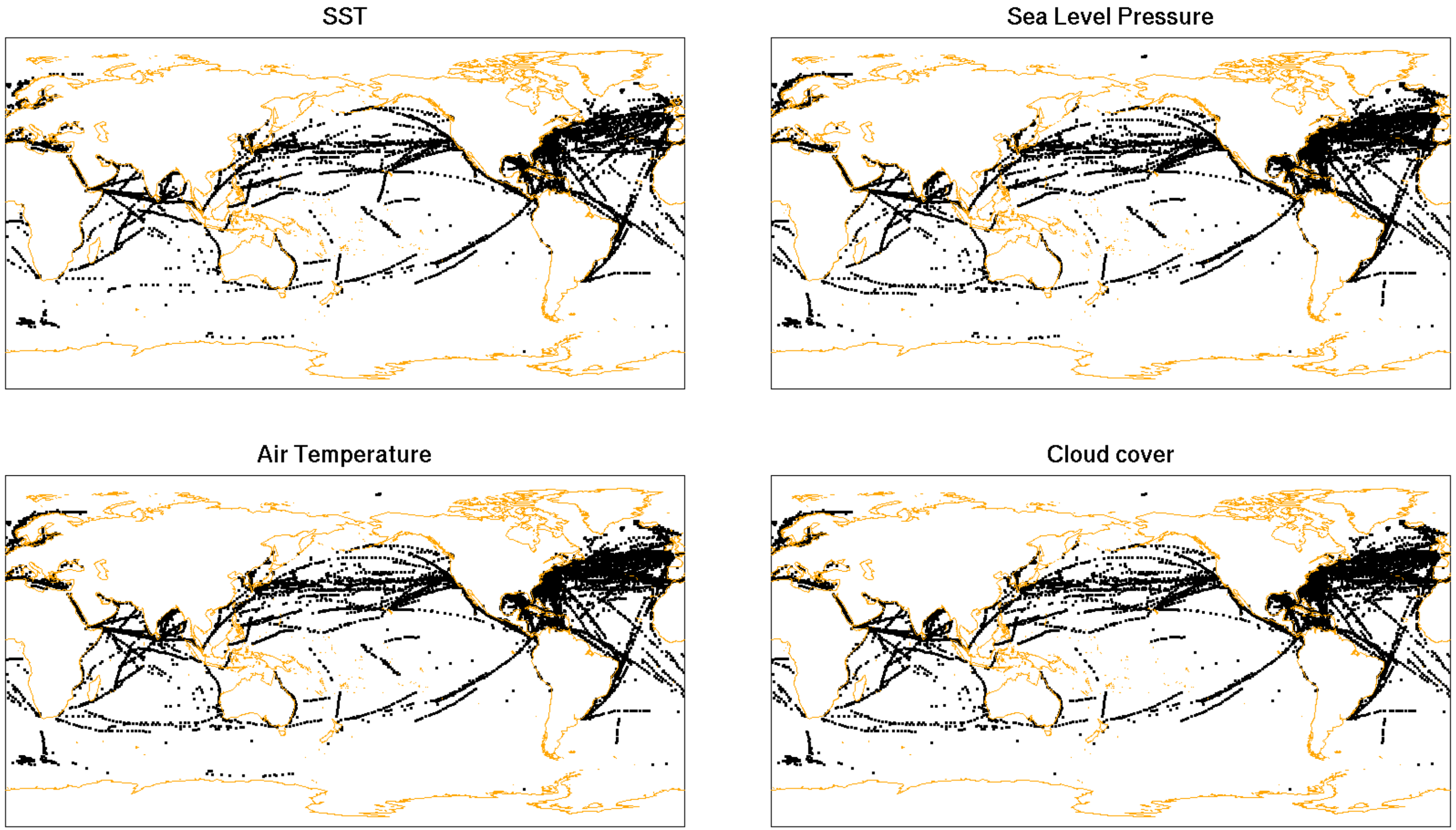
Available observations



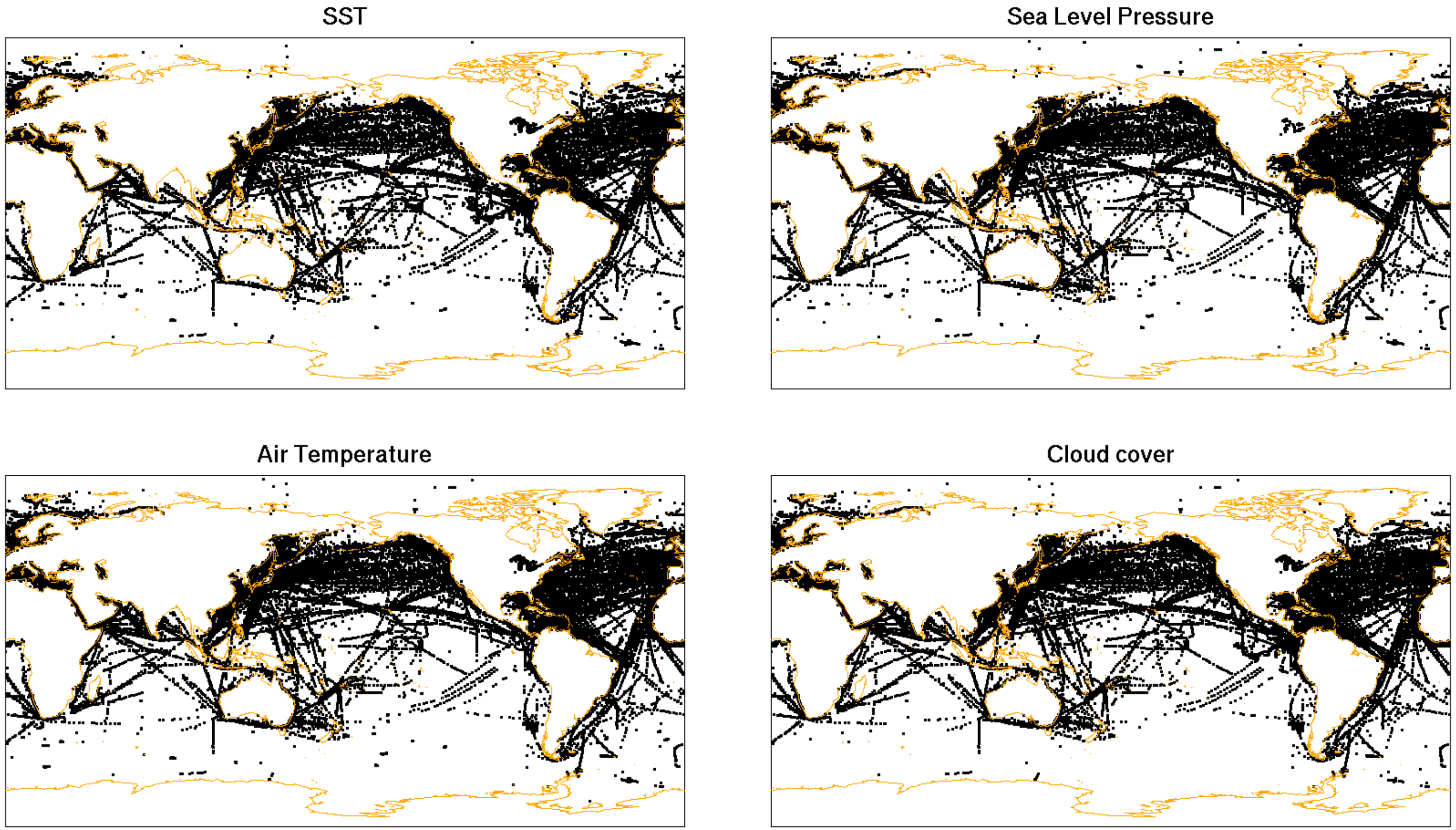
Observations – 1st week December 1880

- From ICOADS
- Freeman et al. 2017. ICOADS Release 3.0, International Journal of Climatology, doi:10.1002/joc.4775



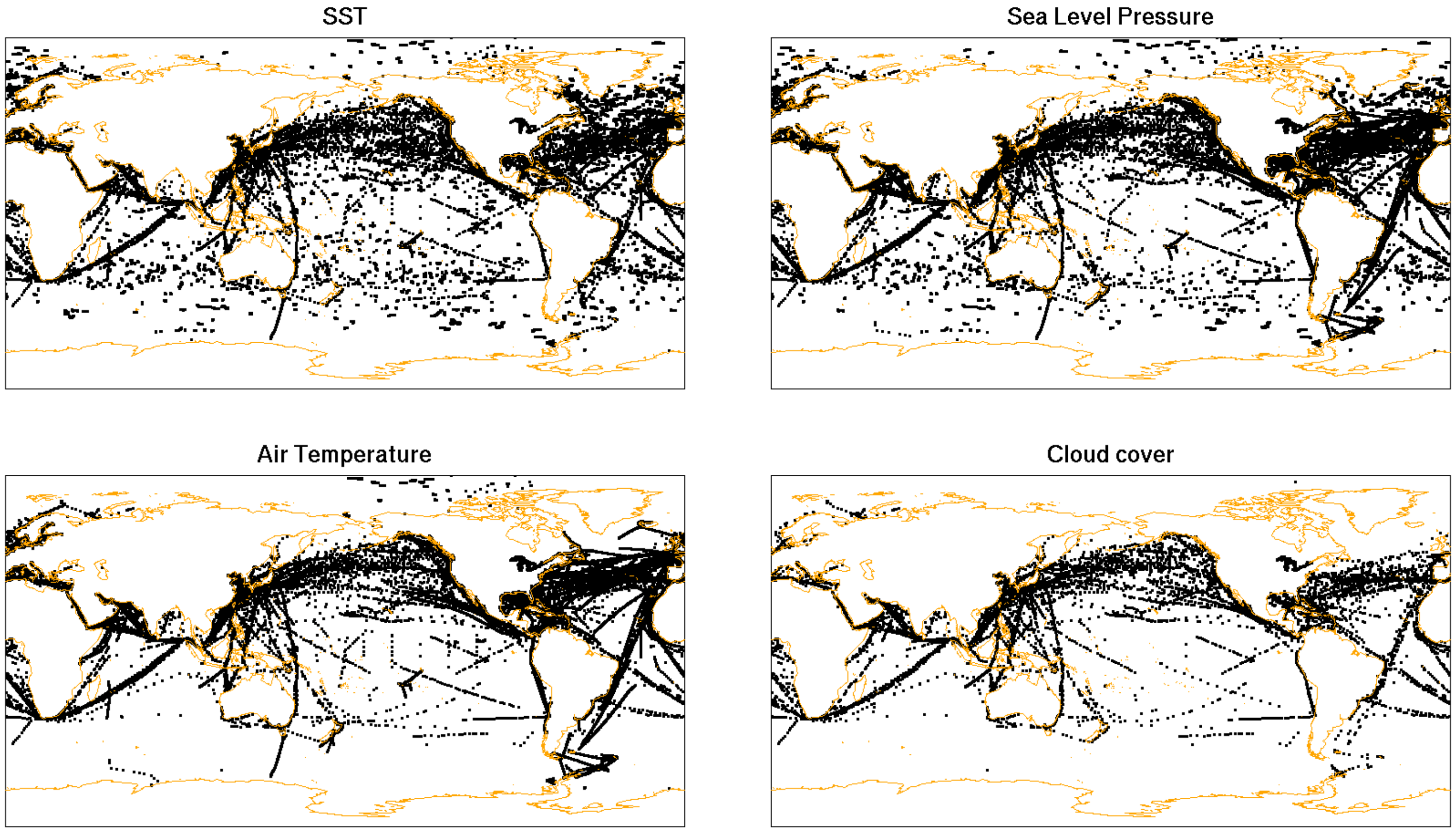
Observations – 1st week December 1950

- From ICOADS
- Freeman et al. 2017. ICOADS Release 3.0, International Journal of Climatology, doi:10.1002/joc.4775



Observations – 1st week December 1990

- From ICOADS
- Freeman et al. 2017. ICOADS Release 3.0, International Journal of Climatology, doi:10.1002/joc.4775

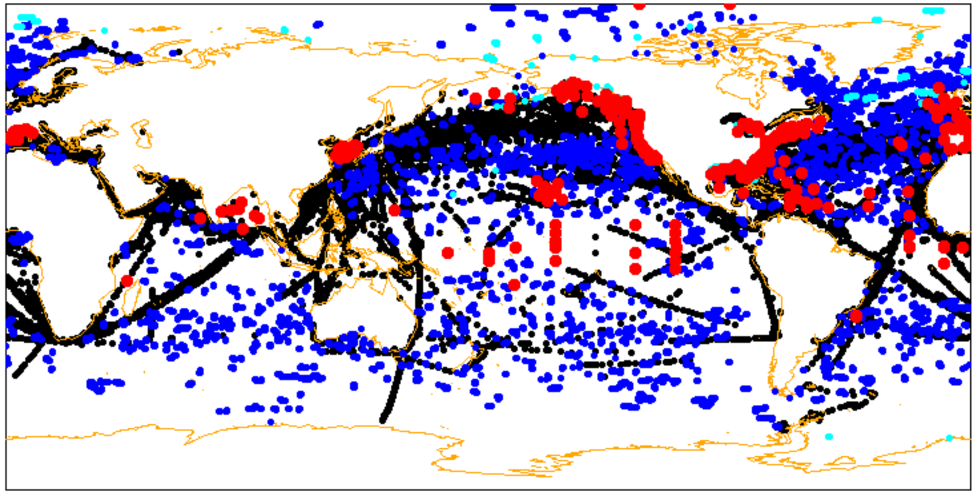


16% of ship observatons

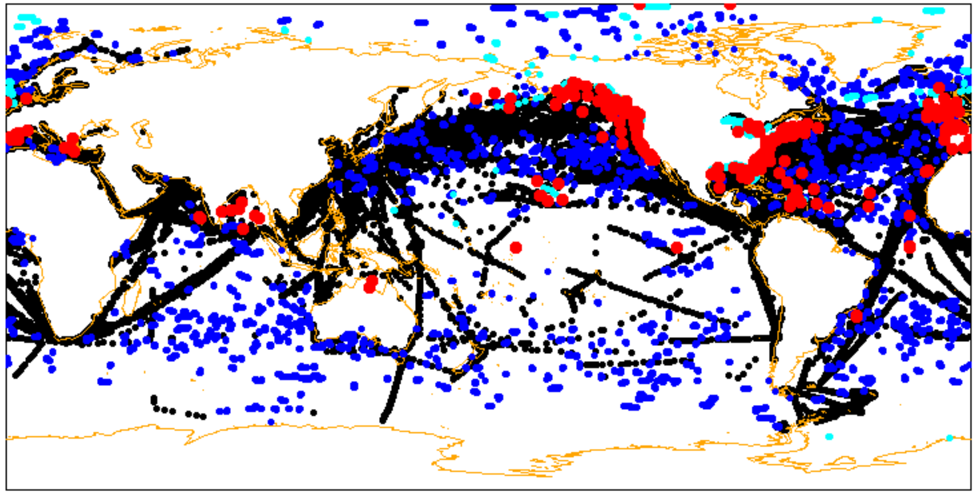
Observations – 1st week December 2021

- From ICOADS R3.0.2
- Liu et al. in review.

SST



Sea Level Pressure



Observations – 1st week December 2021 (by platform type)

- From ICOADS R3.0.2
- Black = ship; red = moored buoy; green = drifter; cyan = other (rig, platform, tide gauge)

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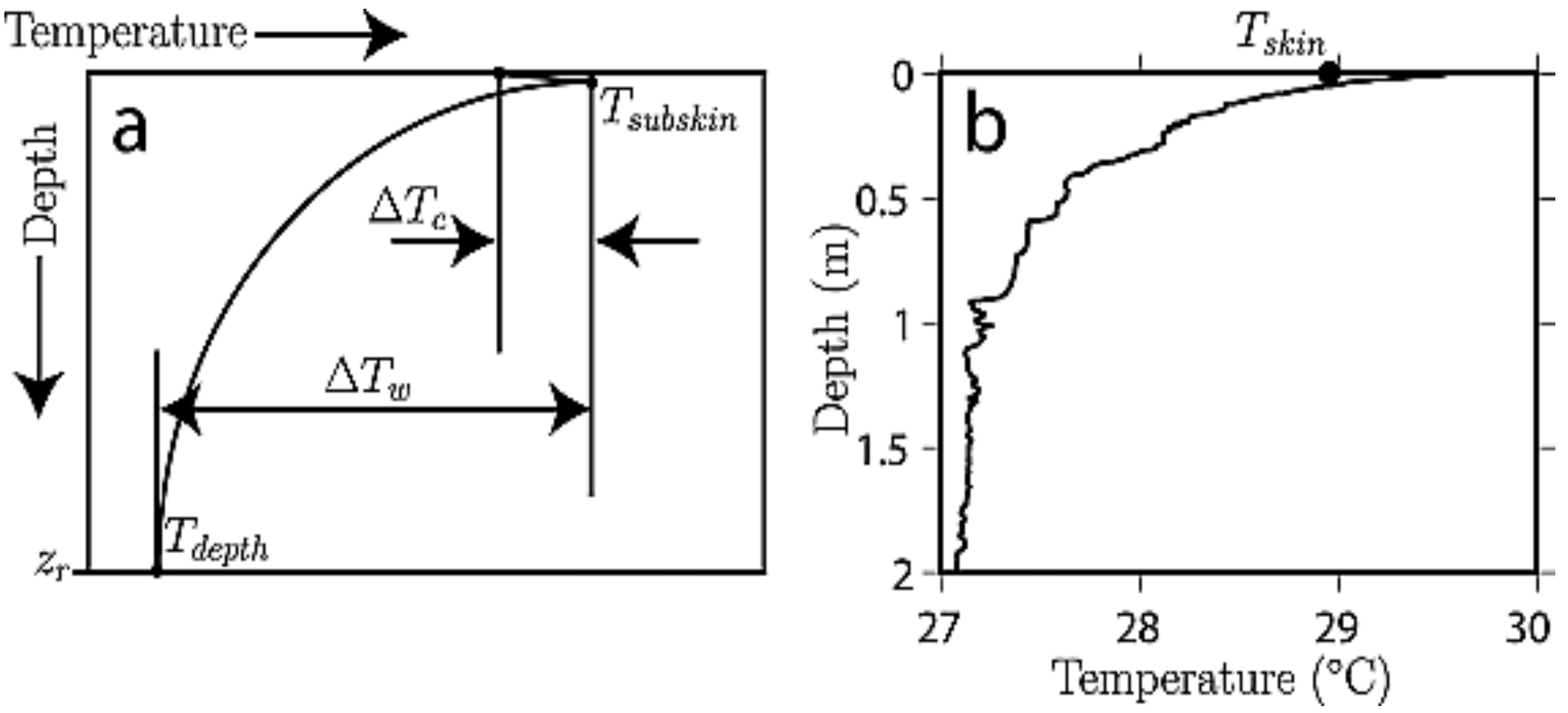
Near-surface temperature variability & air-sea fluxes

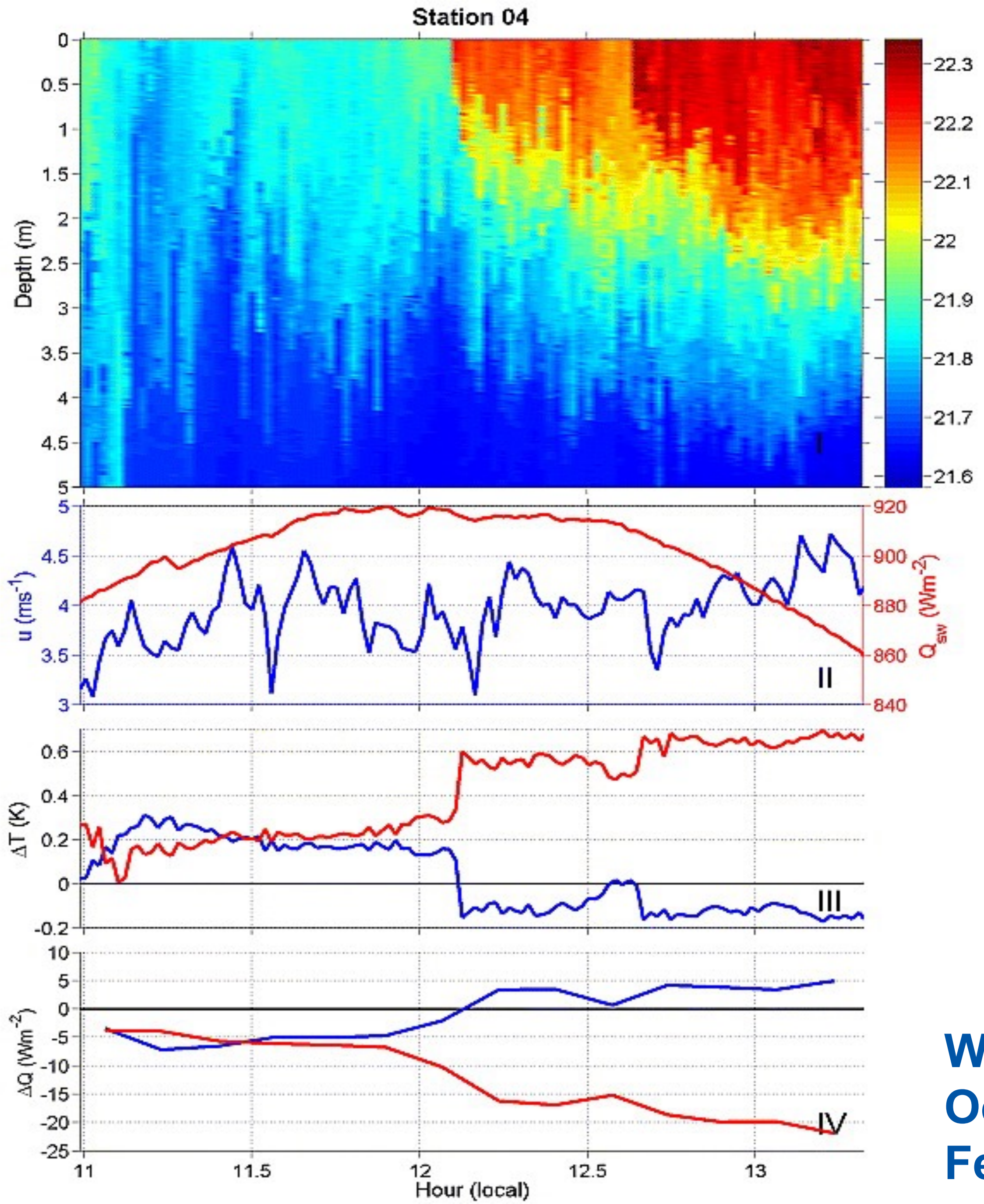
Sea Surface Temperature (SST) Forcing in Reanalysis

- How are SST data and products used?
- For atmospheric reanalyses the SST forms the lower boundary
  - It may be modified (e.g. bulk to skin)
  - Or perturbed to give an ensemble capturing likely uncertainties
- For ocean and coupled reanalyses the surface ocean temperature is likely "nudged" toward the SST field
- Long reanalyses may not have a consistent SST record
  - 20CRv3: SODAsi.v3 ➡ HadISST2
  - MERRA/2: Hurrell et al. (2008) ➡ OISST
- How to represent variability with sparse observations?
  - Ensembles – representing data uncertainty
  - … and missing variability



(a) Schematic showing the vertical temperature structure in the upper few meters of the ocean under conditions of diurnal warming. This is a schematic representation of the model from Fairall et al. [1996a].
(b) Actual profile taken in the upper 2 m with SkinDeEP during station 10. The solid circle indicates the radiometric temperature measurement of Tskin from the M-AERI

Ward (2006), Near-surface ocean temperature, Journal of Geophysical Research: Oceans, Volume: 111, Issue: C2, First published: 11 February 2006, DOI: (10.1029/2004JC002689)



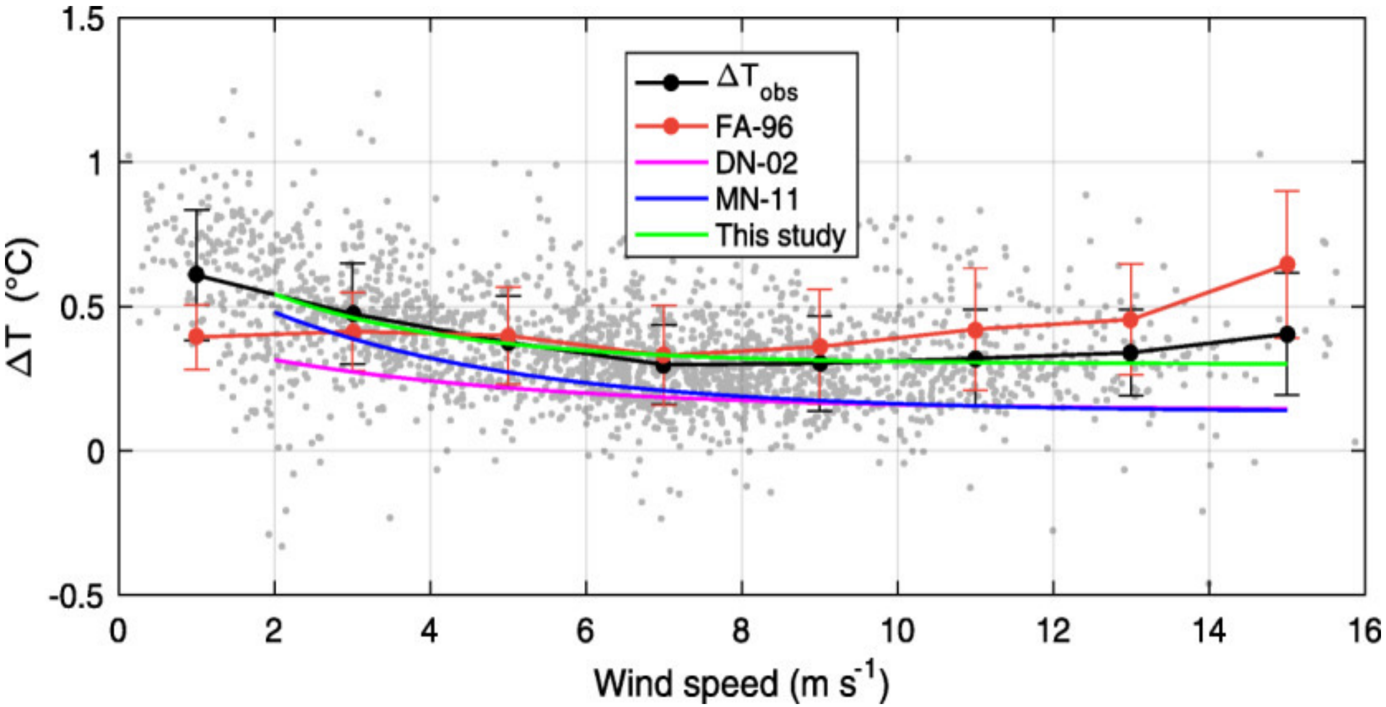
Temperature-depth measurements from SkinDeEP (graph I).

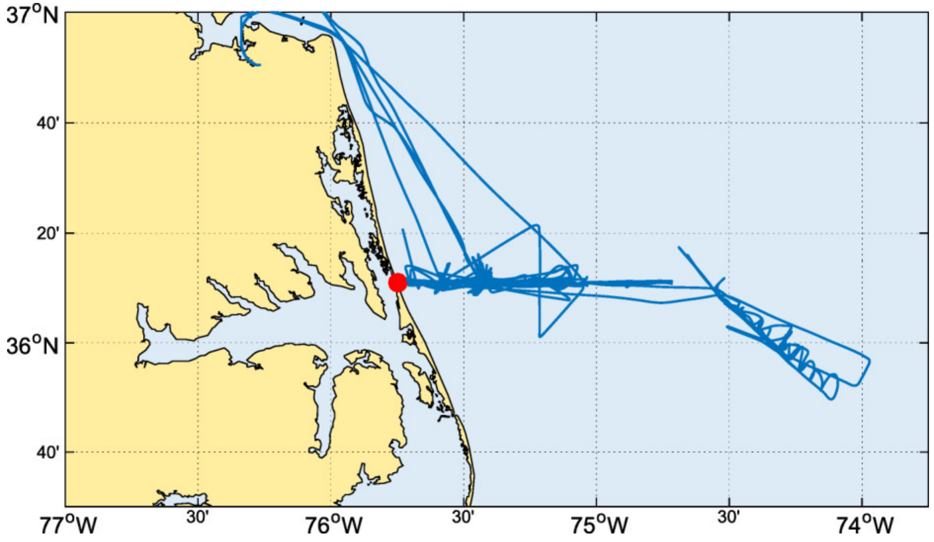
Wind speed (u) and downwelling shortwave radiation (Qsw) (graph II).

Temperature differences: ΔTc (blue), ΔTw (red), and ΔTcw (green) (graph III).

Heat loss errors: ΔQc (blue), ΔQw (red) (graph IV).

Ward (2006), Near-surface ocean temperature, JGR: Oceans, Volume: 111, Issue: C2, First published: 11 February 2006, DOI: (10.1029/2004JC002689)



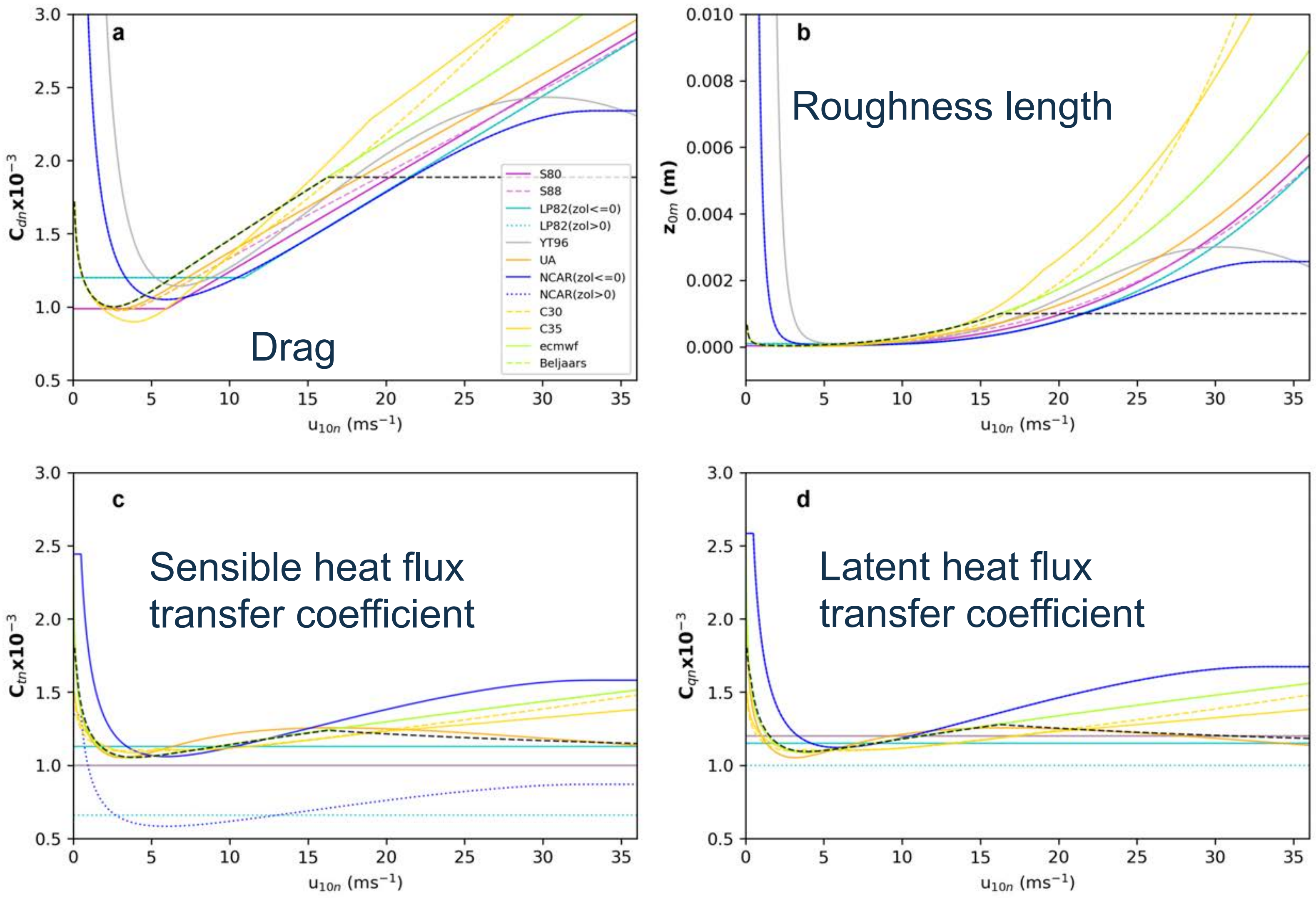


Models tested:
Fairall et al. (1996), JGR
Donlon et al. (2002), JClim
Minnett et al. (2011), DSR-II

Alappattu, D. P., Wang, Q., Yamaguchi, R., Lind, R. J., Reynolds, M., and Christman, A. J. (2017), Warm layer and cool skin corrections for bulk water temperature measurements for air-sea interaction studies, J. Geophys. Res. Oceans, 122, 6470– 6481, doi:10.1002/2017JC012688.

Uncertainty in air-sea exchange parameterisations

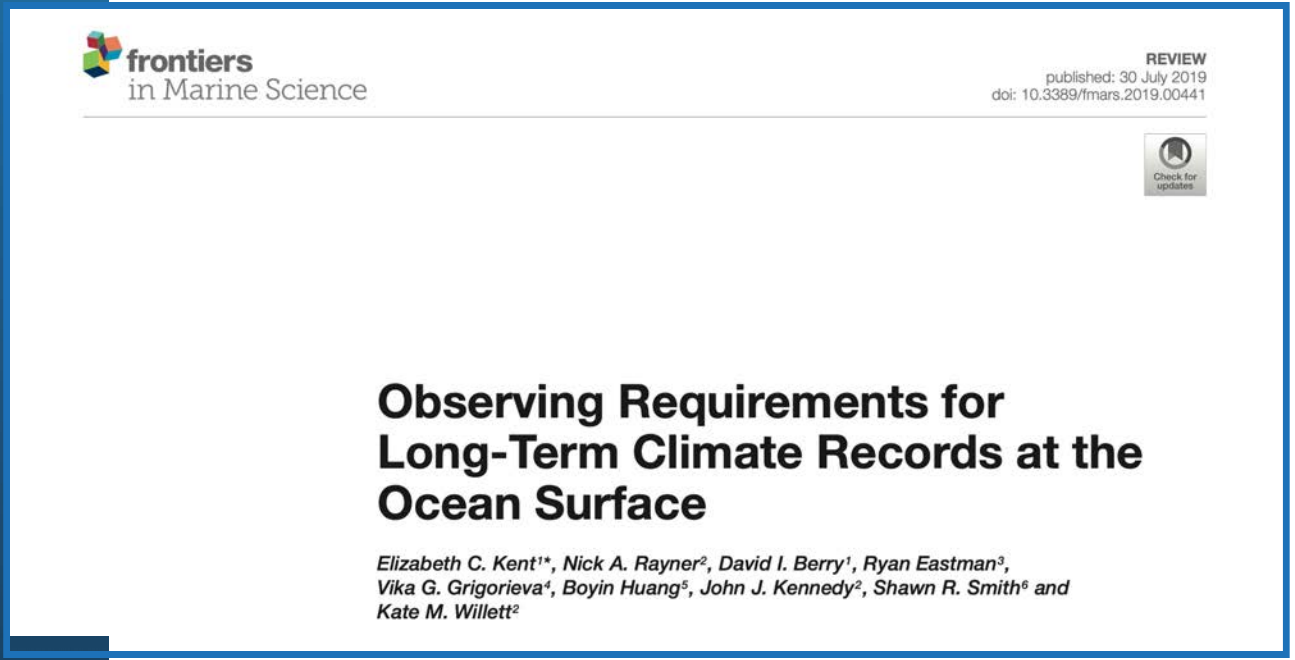
- Exchange coefficient vary at all wind speeds
  - Especially high & low winds
- Some tuned to bulk temperature, some to skin
- Will affect accuracy of air-sea fluxes in single domain analyses
- One contribution to uncertainty in coupled reanalyses



From: Biri et al. (in prep) – Frontiers in Marine Science

Construction of data products

Climate data products

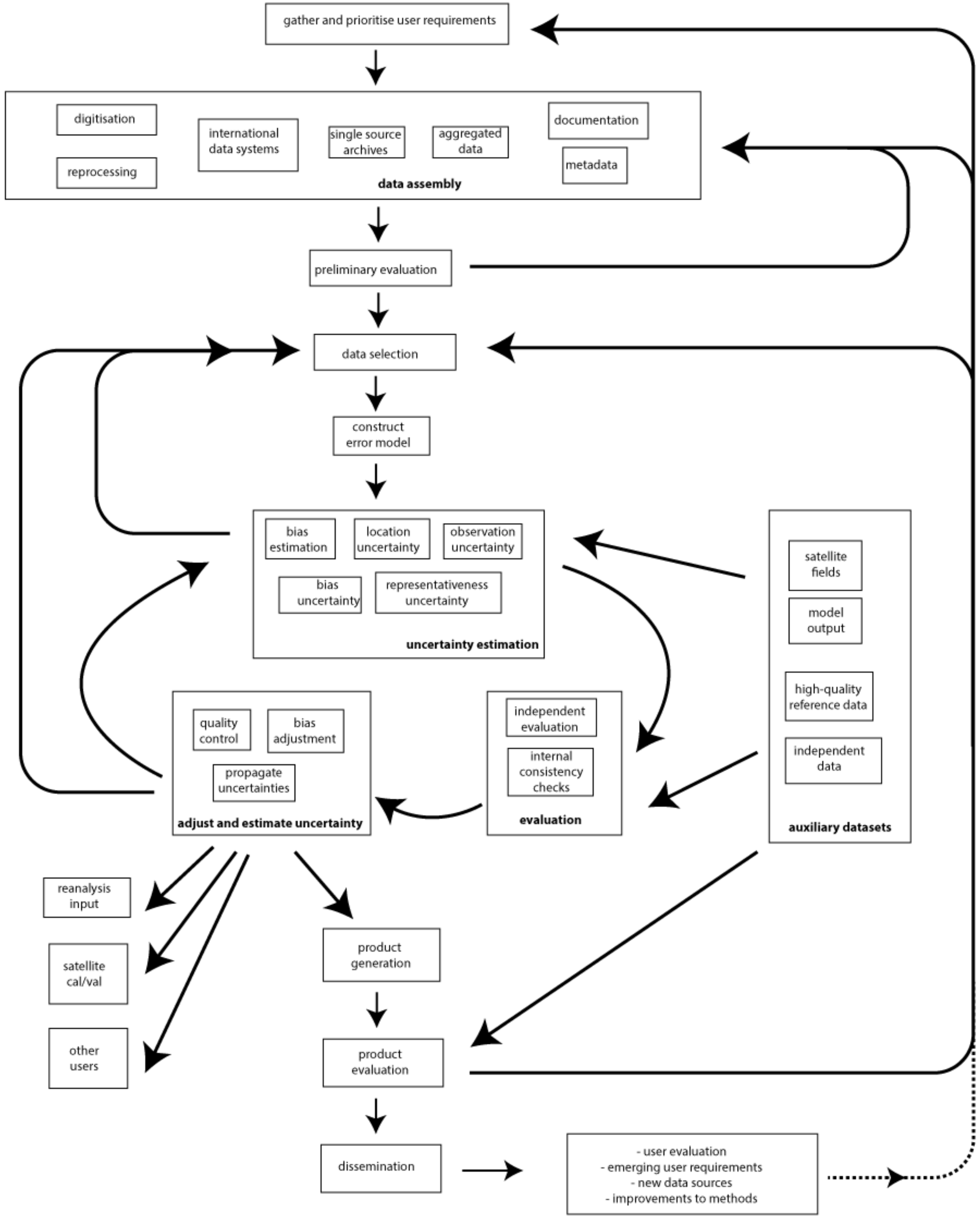

frontiers in Marine Science

REVIEW
published: 30 July 2019
doi: 10.3389/fmars.2019.00441

Check for updates

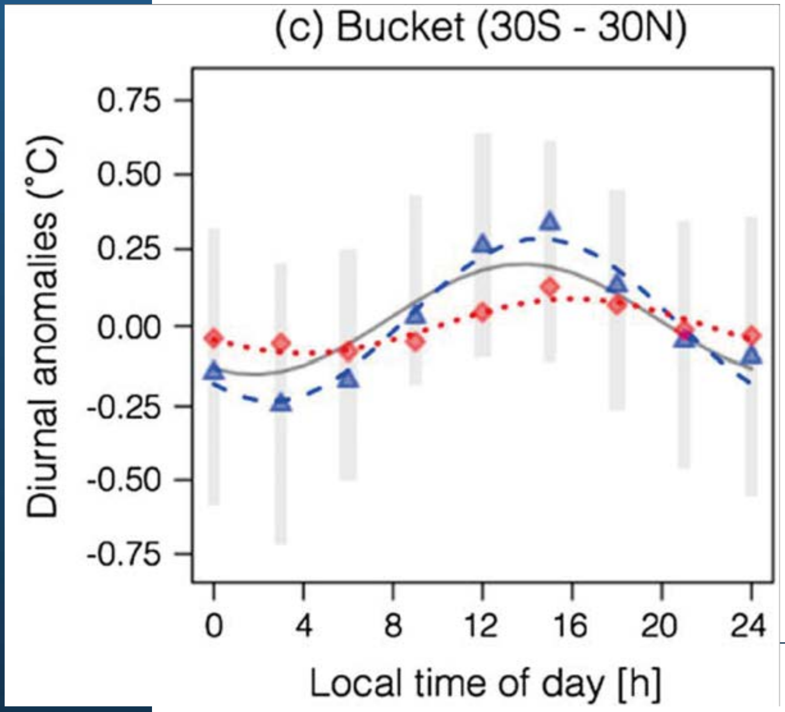
Observing Requirements for Long-Term Climate Records at the Ocean Surface

Elizabeth C. Kent[1], Nick A. Rayner[2], David I. Berry[1], Ryan Eastman[3], Vika G. Grigorieva[4], Boyin Huang[5], John J. Kennedy[2], Shawn R. Smith[6] and Kate M. Willett[2]*



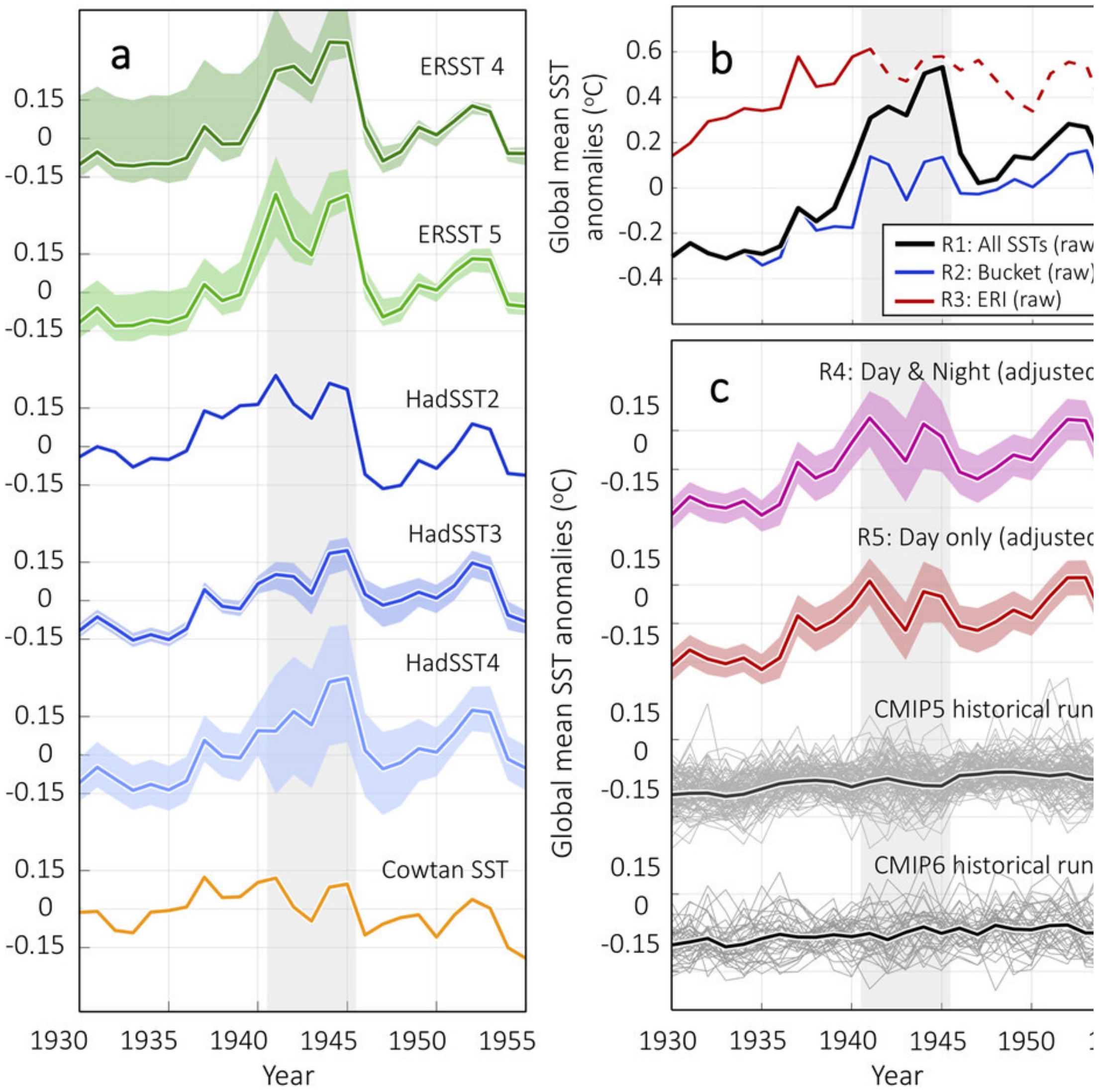
Pervasive biases in long-term SST

- SST data products have residual biases – data for World War 2 remains hard to adjust
- Difference in diurnal cycles between different observation types is key



Carella et al (2018). Estimating SST measurement methods using characteristic differences in the diurnal cycle. *GRL*, 45, 363– 371.

Blue = bucket
Red = expected (drifters)
Black = residual



Chan, D., & Huybers, P. (2021). Correcting Observational Biases in SST Observations Removes Anomalous Warmth during World War II, JClim, 34, 4585-4602.

Diurnal biases in measured air temperature from 16 ships

- Lines are different latitudes, shading 2-σ
  - Red = 25˚N
  - Green = 50˚N
  - Blue = 65˚N
- Bias estimate for each ship, depends on
  - Cloud cover (estimate solar)
  - Relative wind speed
- Bias adjustment requires:
  - Environmental information
    - Cloud cover, wind speed
  - Metadata
    - Vessel speed & course
  - Works best for long tracks

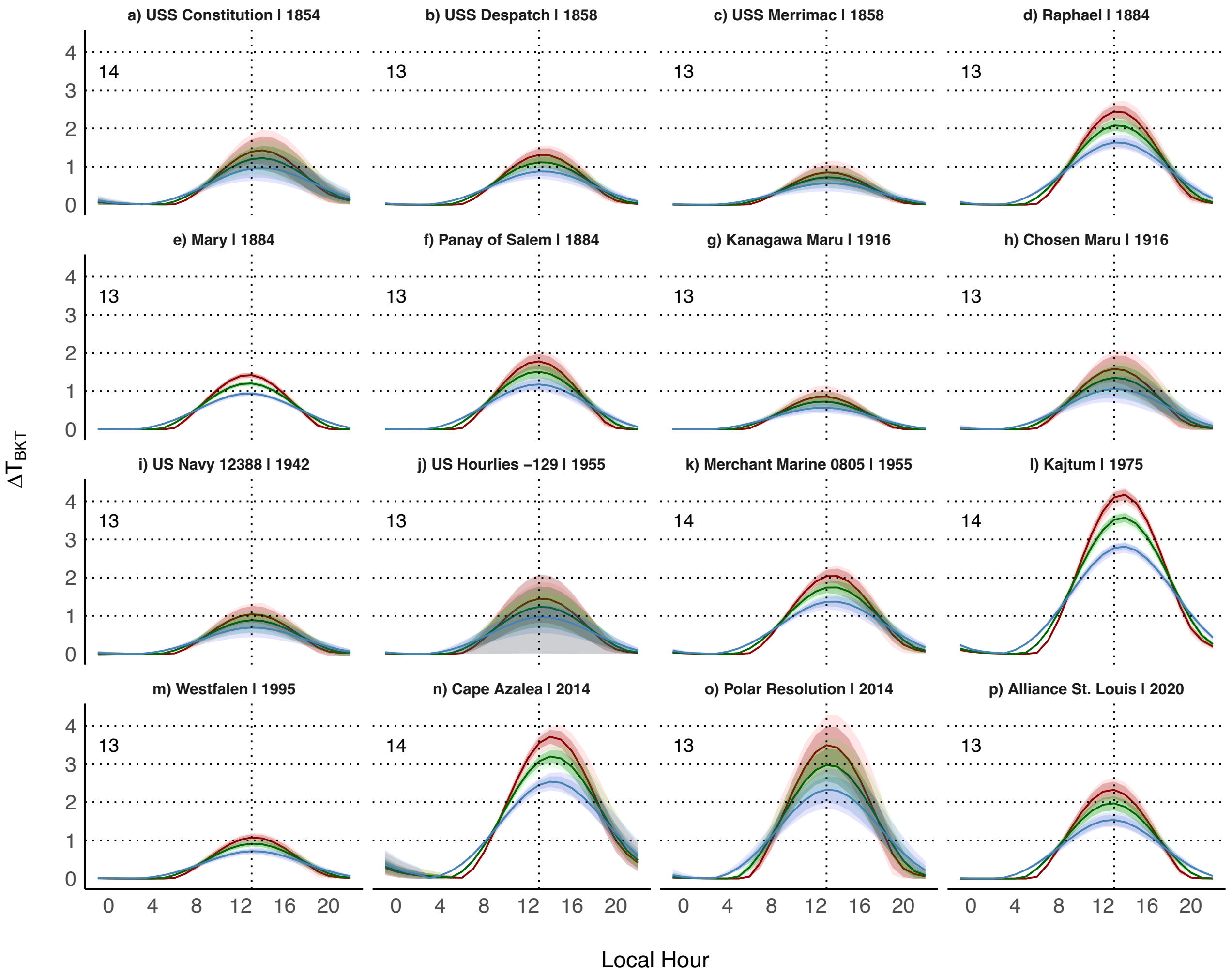
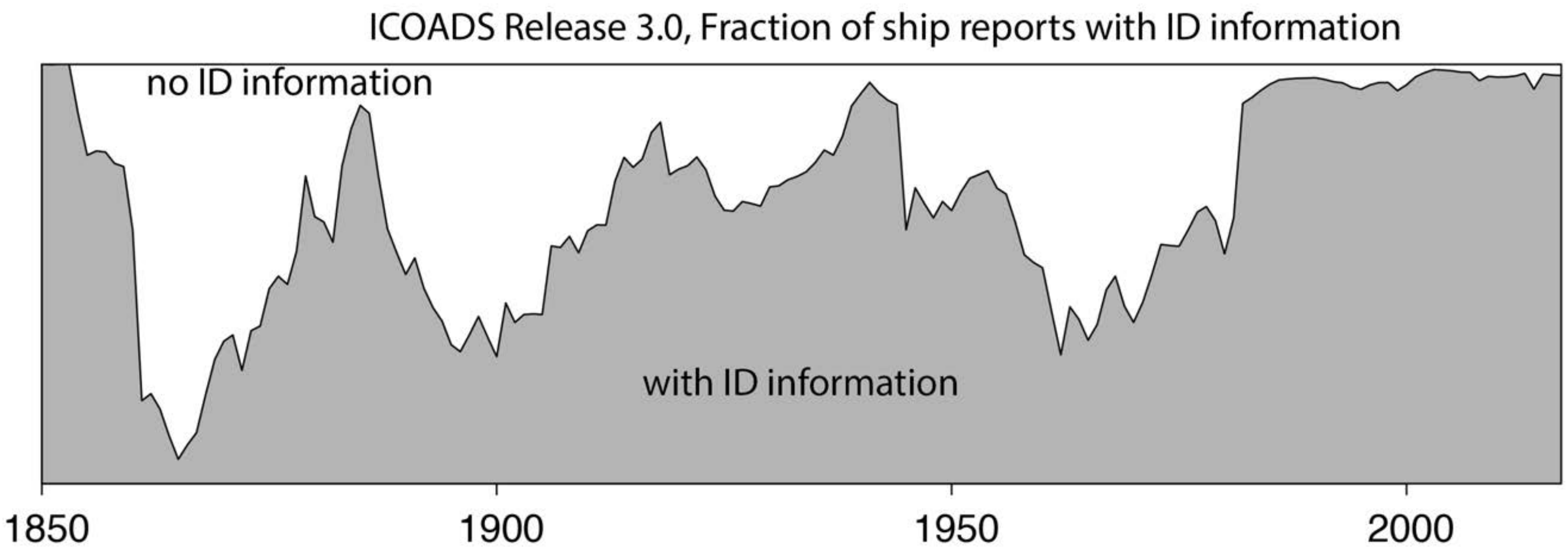
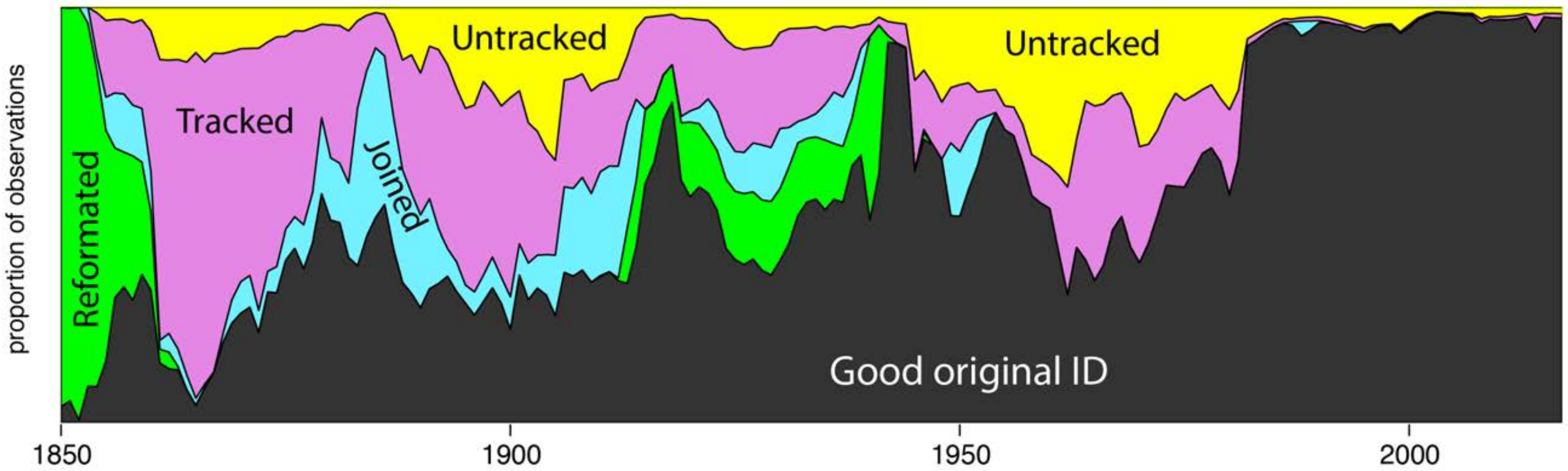


Figure by Tom Cropper, NOC

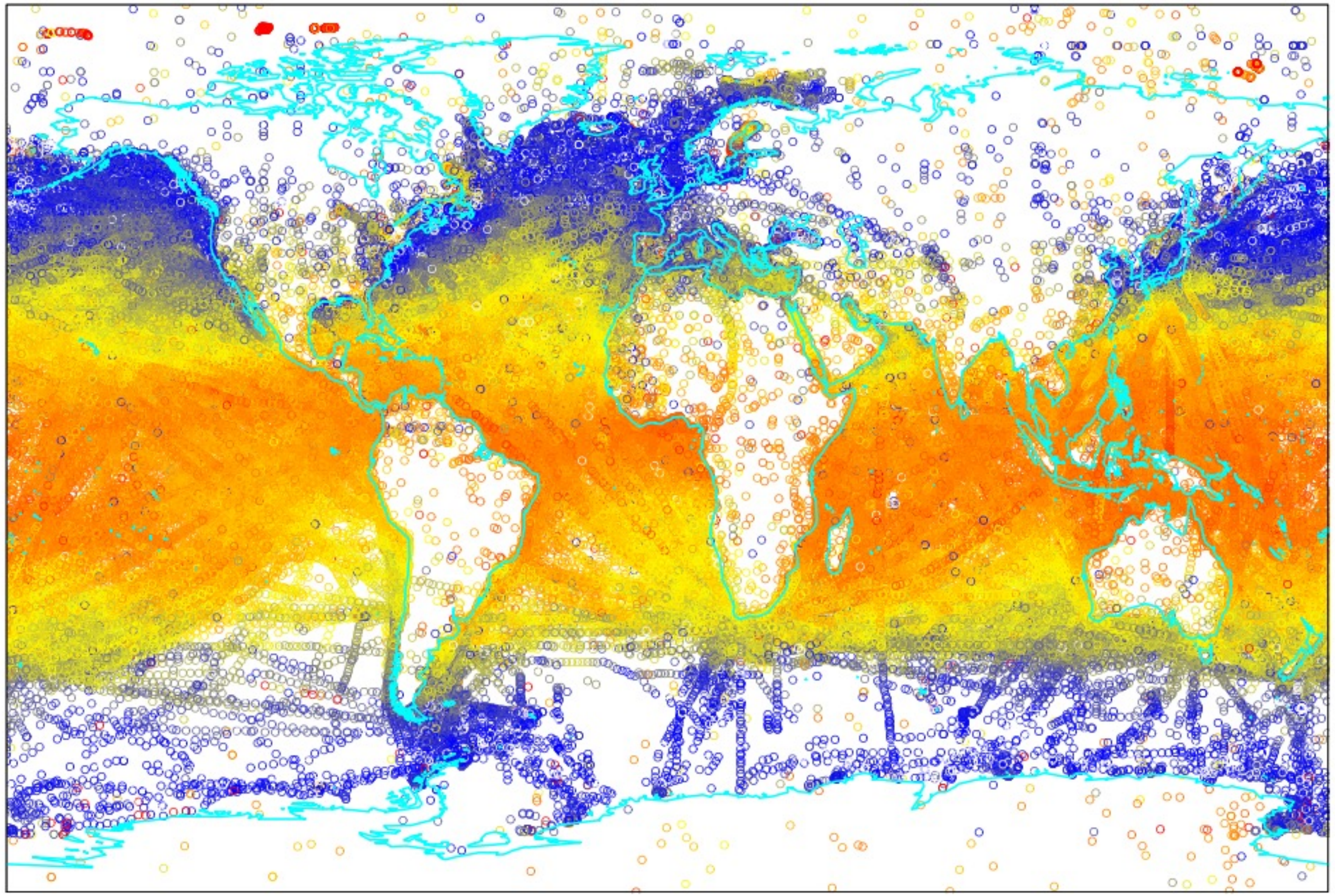




- Benefits for reanalysis include per-ship bias identification
- Better gridded products with more realistic uncertainty estimation
- What to do with untracked obs?

Carella, G., E. C. Kent and D. I. Berry, 2017: A probabilistic approach to ship voyage reconstruction in ICOADS, *International Journal of Climatology*, 37, 2233–2247. doi:10.1002/joc.4492

Tracking works badly at start of Global Telecommunications System

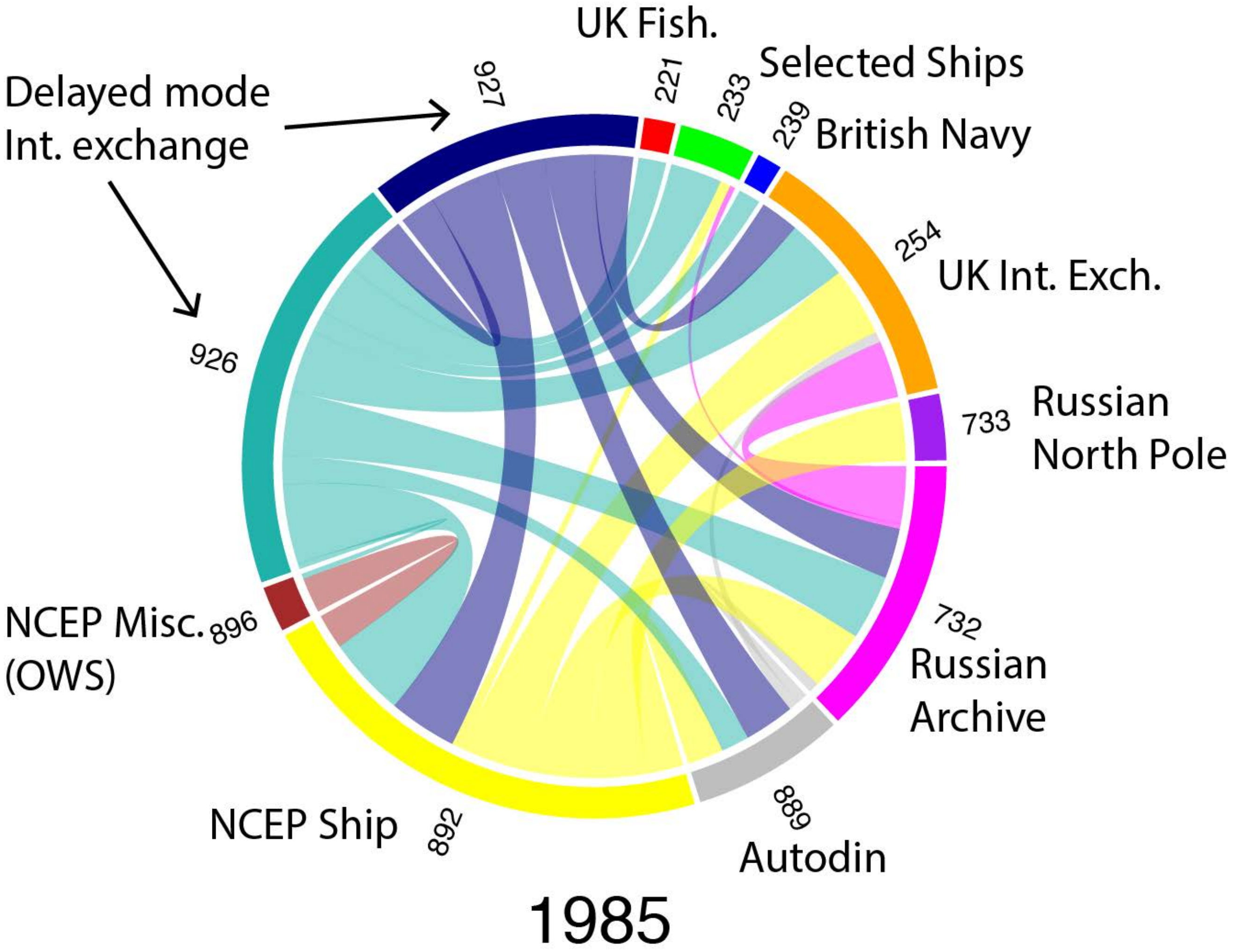


Raw data from
"Monterey Telecoms"

Coloured by SST

Climate Change

Linkages between data sources- chord diagrams



Links based on:

date/location duplicates
ID links
Track filling

ICOADS

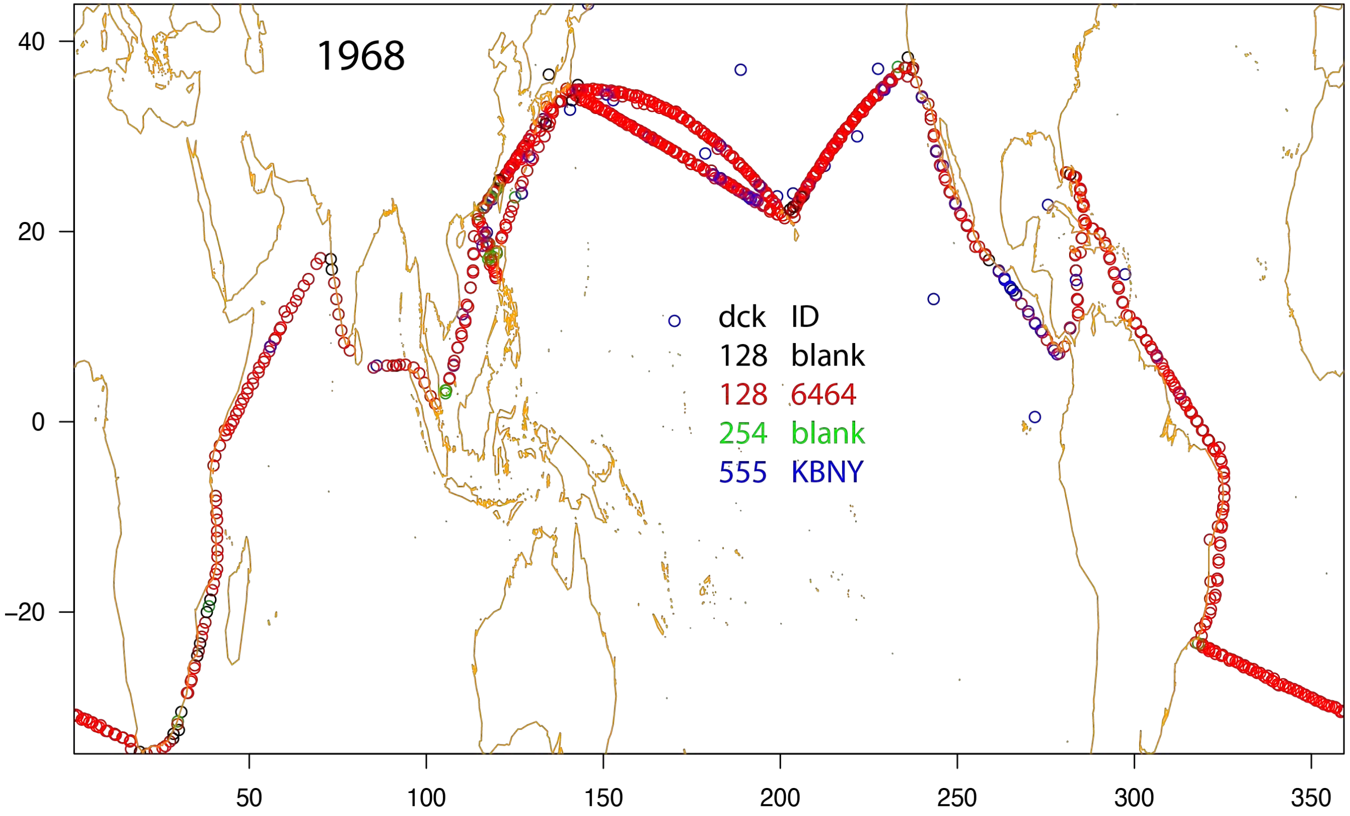
ON BEHALF OF ECMWF FOR THE EUROPEAN COMMISSION

Maynooth University National University of Ireland Maynooth

Inconsistent IDs between sources

- International Comprehensive Ocean-Atmosphere Dataset

- IDs associated via report-level linking
  - Delayed mode ship number
  - Callsign
- Reports with blank IDs associated with track via "gap filling"
- "lost" duplicates: 696 of 936 (75%)
  - Identify inter-source biases?
- New metadata for delayed mode source via Pub. 47



Linking ship/platform IDs enhances metadata

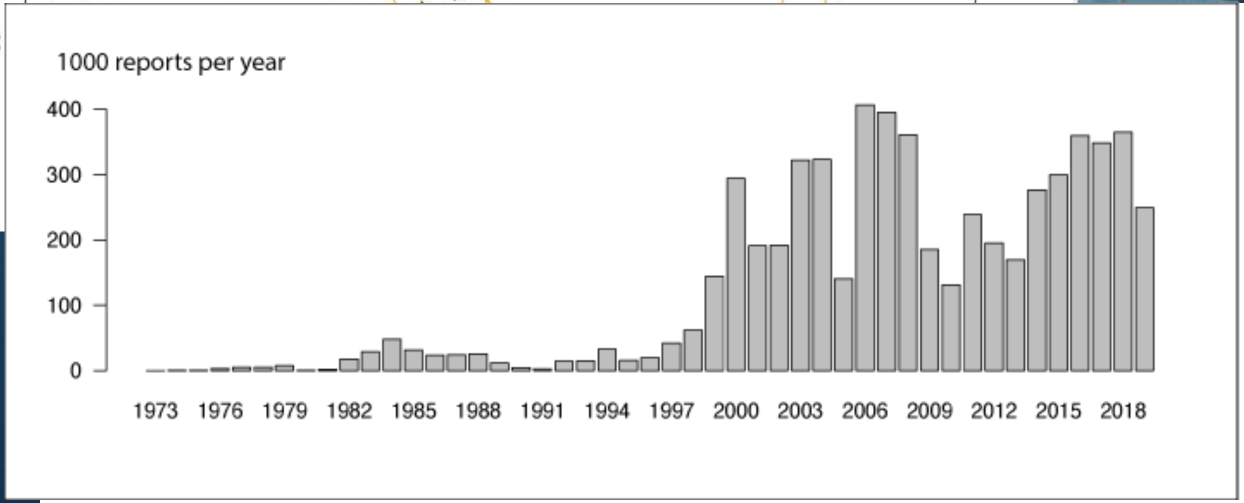
- New metadata
  - USS Franklin Roosevelt
  - Observing height
  - Type of barometer
  - SST measurement method (conflict with ICOADS flags)
  - ….

- Going back and ingesting original data will help us understand the quality of different data sources.

U.S. Navy National Museum of Naval Aviation
photo No. 1996.488.062.039

Potential for observational archive improvements - example

- ICOADS observations from NWP sources flagged as ships may not be ..



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Exam questions

Most-relevant outcomes for reanalysis workshop

- Scientific requirements for a consistent Earth system reanalysis in 2030:
  - Model components and the level of coupling that is feasible to achieve by 2030.

Even for modern-era reanalyses the challenges of resolving or parameterizing gradients near the ocean surface are challenging

Can air-sea flux parameterizatons be tailored to different resolutions?

- Horizontal subgrid-scale variability
- Vertical gradients (and skin/bulk temperature)

Most-relevant outcomes for reanalysis workshop

- Catalogue observational data available to support a consistent climate reanalysis and identify needs for observational data rescue and future observing systems that are needed to support future reanalysis efforts.

Consider needs for evaluation as well as assimilation

Multivariate observations with rich metadata most valuable

Consider granularity of catalogue – some archives are heterogenous

Sampling of diurnal cycle critical

- Needed for coupling
- Identification of solar-related biases (need cloud cover)

Observations that cannot be automated declining in coverage (clouds, weather reports)

Need to accommodate non-standard observations types (data systems, evaluation, QC, metadata)

Observing Requirements for Long-Term Climate Records at the Ocean Surface

Elizabeth C. Kent, Nick A. Rayner, David I. Berry, Ryan Eastman, Vika G. Grigorieva, Boyin Huang, John J. Kennedy, Shawn R. Smith and Kate M. Willett

Observations of conditions at the ocean surface have been made for centuries, contributing to some of the longest instrumental records of climate change. Most prominent is the climate data record (CDR) of sea surface temperature (SST), which is itself essential to the majority of activities in climate science and climate service provision. A much wider range of surface marine observations is available however, providing a rich source of data on past climate. We present a general error model describing the characteristics of observations used for the construction of climate records, illustrating the importance of multi-variate records with rich metadata for reducing uncertainty in CDRs. We describe the data and metadata requirements for the construction of stable, multi-century marine CDRs for variables important for describing the changing climate: SST, mean sea level pressure, air temperature, humidity, winds, clouds, and waves. Available sources of surface marine data are reviewed in the context of the error model. We outline the need for a range of complementary observations, including very high quality observations at a limited number of locations and also observations that sample more broadly but with greater uncertainty. We describe how high-resolution modern records, particularly those of high-quality, can help to improve the quality of observations throughout the historical record. We recommend the extension of internationally-coordinated data management and curation to observation types that do not have a primary focus of the construction of climate records. Also recommended is reprocessing the existing surface marine climate archive to improve and quantify data and metadata quality and homogeneity. We also recommend the expansion of observations from research vessels and high quality moorings, routine observations from ships and from data and metadata rescue. Other priorities include: field evaluation of sensors; resources for the process of establishing user requirements and determining whether requirements are being met; and research to estimate uncertainty, quantify

Ocean Reanalyses: Recent Advances and Unsolved Challenges

Andrea Storto, Aida Alvera-Azcárate, Magdalena A. Balmaseda, Alexander Barth, Matthieu Chevallier, Francois Counillon, Catia M. Domingues, Marie Drevillon, Yann Drillet, Gaël Forget, Gilles Garric, Keith Haines, Fabrice Hernandez, Doroteaciro Iovino, Laura C. Jackson, Jean-Michel Lellouche, Simona Masina, Michael Mayer, Peter R. Oke, Stephen G. Penny, K. Andrew Peterson, Chunxue Yang and Hao Zuo

Ocean reanalyses combine ocean models, atmospheric forcing fluxes, and observations using data assimilation to give a four-dimensional description of the ocean. Metrics assessing their reliability have improved over time, allowing reanalyses to become an important tool in climate services that provide a more complete picture of the changing ocean to end users. Besides climate monitoring and research, ocean reanalyses are used to initialize sub-seasonal to multi-annual predictions, to support observational network monitoring, and to evaluate climate model simulations. These applications demand robust uncertainty estimates and fit-for-purpose assessments, achievable through sustained advances in data assimilation and coordinated inter-comparison activities. Ocean reanalyses face specific challenges: (i) dealing with intermittent or discontinued observing networks, (ii) reproducing inter-annual variability and trends of integrated diagnostics for climate monitoring, (iii) accounting for drift and bias due, e.g., to air-sea flux or ocean mixing errors, and (iv) optimizing initialization and improving performances during periods and in regions with sparse data. Other challenges such as multi-scale data assimilation to reconcile mesoscale and large-scale variability and flow-dependent error characterization for rapidly evolving processes, are amplified in long-term reanalyses. The demand to extend reanalyses backward in time requires tackling all these challenges, especially in the emerging context of earth system reanalyses and coupled data assimilation. This mini-review aims at documenting recent advances from the ocean reanalysis community, discussing unsolved challenges that require sustained activities for maximizing the utility of ocean observations, supporting data rescue and advancing specific research and development requirements for reanalyses.

Keywords: data assimilation, uncertainty, inter-comparisons, observational requirements, historical reanalyses

Global *in situ* Observations of Essential Climate and Ocean Variables at the Air–Sea Interface

Luca R. Centurioni, Jon Turton, Rick Lumpkin, Lancelot Braasch, Gary Brassington, Yi Chao, Etienne Charpentier, Zhaohui Chen, Gary Corlett, Kathleen Dohan, Craig Donlon, Champika Gallage, Verena Hormann, Alexander Ignatov, Bruce Ingleby, Robert Jensen, Boris A. Kelly-Gerreyn, Inga M. Koszalka, Xiaopei Lin, Eric Lindstrom, Nikolai Maximenko, Christopher J. Merchant, Peter Minnett, Anne O'Carroll, Theresa Paluszkiewicz, Paul Poli, Pierre-Marie Poulain, Gilles Reverdin, Xiujun Sun, Val Swail, Sidney Thurston, Lixin Wu, Lisan Yu, Bin Wang and Dongxiao Zhang

The air-sea interface is a key gateway in the Earth system. It is where the atmosphere sets the ocean in motion, climate/weather-relevant air-sea processes occur, and pollutants (i.e., plastic, anthropogenic carbon dioxide, radioactive/chemical waste) enter the sea. Hence, accurate estimates and forecasts of physical and biogeochemical processes at this interface are critical for sustainable blue economy planning, growth, and disaster mitigation. Such estimates and forecasts rely on accurate and integrated *in situ* and satellite surface observations. High-impact uses of ocean surface observations of essential ocean/climate variables (EOVs/ECVs) include (1) assimilation into/validation of weather, ocean, and climate forecast models to improve their skill, impact, and value; (2) ocean physics studies (i.e., heat, momentum, freshwater, and biogeochemical air–sea fluxes) to further our understanding and parameterization of air–sea processes; and (3) calibration and validation of satellite ocean products (i.e., currents, temperature, salinity, sea level, ocean color, wind, and waves). We review strengths and limitations, impacts, and sustainability of *in situ* ocean surface observations of several ECVs and EOVs. We draw a 10-year vision

Air-Sea Fluxes With a Focus on Heat and Momentum

Meghan F. Cronin, Chelle L. Gentemann, James Edson, Iwao Ueki, Mark Bourassa, Shannon Brown, Carol Anne Clayson, Chris W. Fairall, J. Thomas Farrar, Sarah T. Gille, Sergey Gulev, Simon A. Josey, Seiji Kato, Masaki Katsumata, Elizabeth Kent, Marjolaine Krug, Peter J. Minnett, Rhys Parfitt, Rachel T. Pinker, Paul W. Stackhouse Jr., Sebastiaan Swart, Hiroyuki Tomita, Douglas Vandemark, Robert A. Weller, Kunio Yoneyama, Lisan Yu and Dongxiao Zhang

Turbulent and radiative exchanges of heat between the ocean and atmosphere (hereafter heat fluxes), ocean surface wind stress, and state variables used to estimate them, are Essential Ocean Variables (EOVs) and Essential Climate Variables (ECVs) influencing weather and climate. This paper describes an observational strategy for producing 3-hourly, 25-km (and an aspirational goal of hourly at 10-km) heat flux and wind stress fields over the global, ice-free ocean with breakthrough 1-day random uncertainty of 15 W m^{-2} and a bias of less than 5 W m^{-2}. At present this accuracy target is met only for OceanSITES reference station moorings and research vessels (RVs) that follow best practices. To meet these targets globally, in the next decade, satellite-based observations must be optimized for boundary layer measurements of air temperature, humidity, sea surface temperature, and ocean wind stress. In order to tune and validate these satellite measurements, a complementary global *in situ* flux array, built around an expanded OceanSITES network of time series reference station moorings, is also needed. The array would include 500–1000 measurement platforms, including autonomous surface vehicles, moored and drifting buoys, RVs, the existing OceanSITES network of 22 flux sites, and new OceanSITES expanded in 19 key regions. This array would be globally distributed, with 1–3 measurement platforms in each nominal 10° by 10° box. These improved moisture and temperature profiles and surface data, if assimilated into Numerical Weather Prediction (NWP) models, would lead to better representation of cloud formation processes, improving state variables and surface radiative and turbulent fluxes from these models. The *in situ* flux array provides globally distributed measurements and metrics for satellite algorithm development,

Observational Needs for Improving Ocean and Coupled Reanalysis, S2S Prediction, and Decadal Prediction

Stephen G. Penny, Santha Akella, Magdalena A. Balmaseda, Philip Browne, James A. Carton, Matthieu Chevallier, Francois Counillon, Catia Domingues, Sergey Frolov, Patrick Heimbach, Patrick Hogan, Ibrahim Hoteit, Doroteaciro Iovino, Patrick Laloyaux, Matthew J. Martin, Simona Masina, Andrew M. Moore, Patricia de Rosnay, Dinand Schepers, Bernadette M. Sloyan, Andrea Storto, Aneesh Subramanian, SungHyun Nam, Frederic Vitart, Chunxue Yang, Yosuke Fujii, Hao Zuo, Terry O'Kane, Paul Sandery, Thomas Moore and Christopher C. Chapman

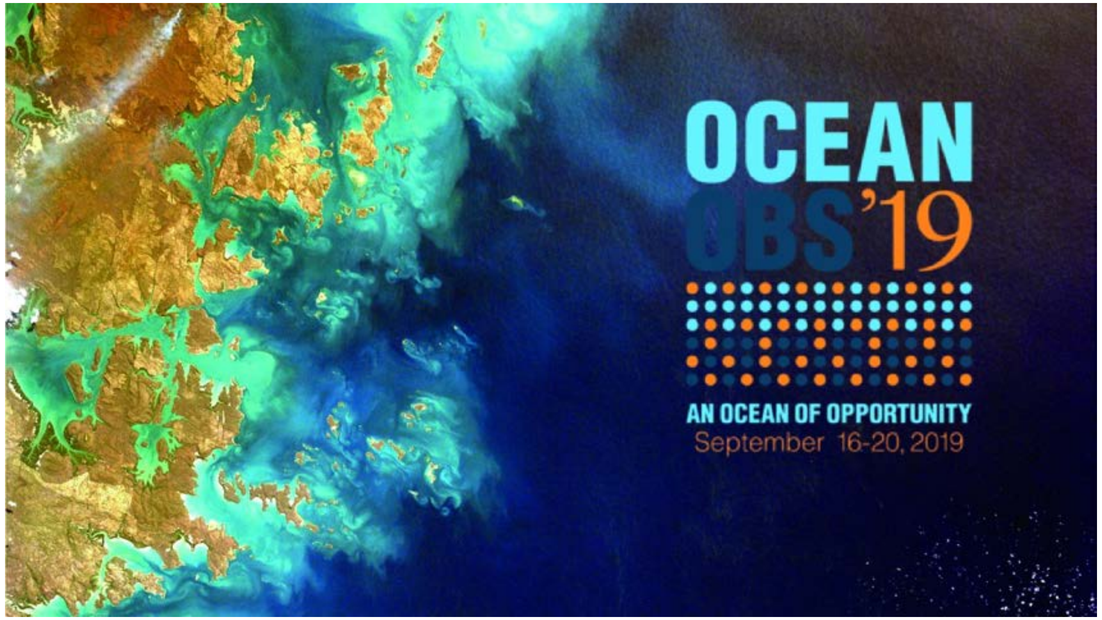
Developments in observing system technologies and ocean data assimilation (DA) are symbiotic. New observation types lead to new DA methods and new DA methods, such as coupled DA, can change the value of existing observations or indicate where new observations can have greater utility for monitoring and prediction. Practitioners of DA are encouraged to make better use of observations that are already available, for example, taking advantage of strongly coupled DA so that ocean observations can be used to improve atmospheric analyses and vice versa. Ocean reanalyses are useful for the analysis of climate as well as the initialization of operational long-range prediction models. There are many remaining challenges for ocean reanalyses due to biases and abrupt changes in the ocean-observing system throughout its history, the presence of biases and drifts in models, and the simplifying assumptions made in DA solution methods. From a governance point of view, more support is needed to bring the ocean-observing and DA communities together. For prediction applications, there is wide agreement that protocols are needed for rapid communication of ocean-observing data on numerical weather prediction (NWP) timescales. There is potential for new observation types to enhance the observing system by supporting prediction on multiple timescales, ranging from the typical timescale of NWP, covering hours to weeks, out to multiple decades. Better communication between DA and observing communities is encouraged in order to allow operational prediction centers the ability to provide guidance for the design of a sustained and adaptive observing network.

Keywords: data assimilation, reanalysis, coupled data assimilation, S2S prediction, decadal prediction, ocean observation network, ocean data assimilation, ocean reanalysis

Observational Needs of Sea Surface Temperature

Anne G. O'Carroll, Edward M. Armstrong, Helen M. Beggs, Marouan Bouali, Kenneth S. Casey, Gary K. Corlett, Prasanjit Dash, Craig J. Donlon, Chelle L. Gentemann, Jacob L. Høyer, Alexander Ignatov, Kamila Kabobah, Misako Kachi, Yukio Kurihara, Ioanna Karagali, Eileen Maturi, Christopher J. Merchant, Salvatore Marullo, Peter J. Minnett, Matthew Pennybacker, Balaji Ramakrishnan, RAAJ Ramsankaran, Rosalia Santoleri, Swathy Sunder, Stéphane Saux Picart, Jorge Vázquez-Cuervo and Werenfrid Wimmer

Sea surface temperature (SST) is a fundamental physical variable for understanding, quantifying and predicting complex interactions between the ocean and the atmosphere. Such processes determine how heat from the sun is redistributed across the global oceans, directly impacting large- and small-scale weather and climate patterns. The provision of daily maps of global SST for operational systems, climate modeling and the broader scientific community is now a mature and sustained service coordinated by the Group for High Resolution Sea Surface Temperature (GHRSST) and the CEOS SST Virtual Constellation (CEOS SST-VC). Data streams are shared, indexed, processed, quality controlled, analyzed, and documented within a Regional/Global Task Sharing (R/GTS) framework, which is implemented internationally in a distributed manner. Products rely on a combination of low-Earth orbit infrared and microwave satellite imagery, geostationary orbit infrared satellite imagery, and *in situ* data from moored and drifting buoys, Argo floats, and a suite of independent, fully characterized and traceable *in situ* measurements for product validation (Fiducial Reference Measurements, FRM). Research and development continues to tackle problems such as instrument calibration, algorithm development, diurnal variability, derivation of high-quality skin and depth temperatures, and areas of specific interest such as the high latitudes and coastal areas. In this white paper, we review progress versus the challenges we set out 10 years ago in a previous paper, highlight remaining and new research and development challenges for the next 10 years



Identify priorities for data rescue and reprocessing

Build a data system for rescued and reprocessed data that retains all recorded information

- Archive data as recorded before translation/conversion/correction
- Evaluation of data sources in ICOADS, preprocess, rebuild the archive

Open-source tools for translations, QC, corrections, evaluation, comparisons

Multi-variate data most valuable, retain & embed all documentation, metadata, logbook images

Data that resolve the diurnal cycle

For marine data value of very-sparse data is hard to assess

Compare data sources

- Duplicates – same original data with different histories
- Buddies – nearby data from different sources

Opportunities for collaboration (1)

- Requirements for joint infrastructure (JEDI, observation sharing, diagnostic sharing).
- Requires excellent data provenance
- Unique observation identifiers – ideally from data providers
- Opportunities for shared experimentation
- Code to allow users to run off-line or embedded analyses for testing
- Value of newly-rescued observations or new data types
- Outreach with aligned PhD studentships & researchers outside reanalysis centres
    - Projects designed to answer key questions with help and support from reanalysis centres
- Collaboration between reanalysis producers.
- Consistent outputs

Opportunities for collaboration (2)

- Collaboration between climate modeling/data products communities and reanalysis producers.
- Provision of output in forms that are easy to use:
  - Monthly means, including variables with non-linear relationships (e.g. relative humidity, specific humidity, dewpoint temperature), 10m values over the ocean
  - Gridded output for direct comparison with data products
    - Monthly and daily means
    - Land, ocean (ice masks), combined
    - 5˚, 2˚ 1˚ resolution (and regridding tools)
  - Variables for height adjustment and surface exchange at native resolution
    - u*, t*, q*, z/L, ρ, cd, ct, cq, zo, zot, zoq
- Embed bias adjustments and QC into reanalyses (needs improvements to solar estimates)
- Data withholding?

Future of reanalysis – surface marine perspective

- What do you see are the most significant advances for the field of reanalysis in 5-10 years?
  - Potential for increased use of reanalysis output to assess & improve observations and data products
- What do you see are the most significant barriers to progress in the field of reanalysis?
  - Lack of funding/expertise for data evaluation, bias adjustment and uncertainty estimation
  - Data idiosyncrasies. are a barrier to wider involvement in construction of data products and use of more sophisticated statistical methods
  - How to identify when an observation has been assimilated? – and with what weight?
- Which collaborations are currently working and which collaborations need to be fostered?
  - Fairly good collaboration between reanalyses centres and data providers for SST and pressure
  - Need closer interactions for other surface marine variables.
- What are the critical requirements for consistent Earth system reanalysis?
  - Improvements to data system, feedback from reanalysis, repeat
  - Ability to evaluate reanalyses output
- What observational datasets are required to support these requirements?
  - Multivariate near surface ocean data, multiple platform types (ships, buoys, drifters, Argo, new autonomous platforms, crowd sourced data)
- What modeling components are mature enough to enable reanalysis for your specific science question or application?
- How is uncertainty quantified for your application? Are there significant barriers for quantifying uncertainty in your field?
  - Data comparisons (e.g. variograms, 3-way co-locations)
  - Lack of long-term reference observations

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