Health of the climate observing system II:

The air-sea interface from satellite observations

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US CLIVAR Summit Meeting

August 2017, Baltimore MD

What time/space scales do we need to observe?

Climate-scale: requires accurate observations and long, continuous records

Processes/phenomena: require frequent observations and high resolution

Mesoscale: requires both accuracy and frequency

Measurements needed for air sea interaction

Surface heat flux

Surface freshwater flux

Surface momentum flux

SST / heat content

Measurements needed for air sea interaction

Satellite-based products:

Surface heat flux	**Derived flux components** (turbulent, sensible)
Surface freshwater flux	**Precipitation, evaporation, runoff** (direct)
	Sea surface salinity (integrated flux)
Surface momentum flux	**Wind and current vectors**
SST / heat content	**Sea surface temperature**
	Heat content (altimetry)

Holistic view: how are we doing?

Biggest uncertainties:

- Surface heat fluxes (means, variability, trends)
- Clouds
- High latitudes
- Small scales (submesoscale to mesoscale)
- Issues:
  1. many satellite measurements do not carefully quantify uncertainties or causes thereof.
  2. we don’t have a good quantification of what the impact of these uncertainties are.

Biggest gaps or future gaps in the observing system:

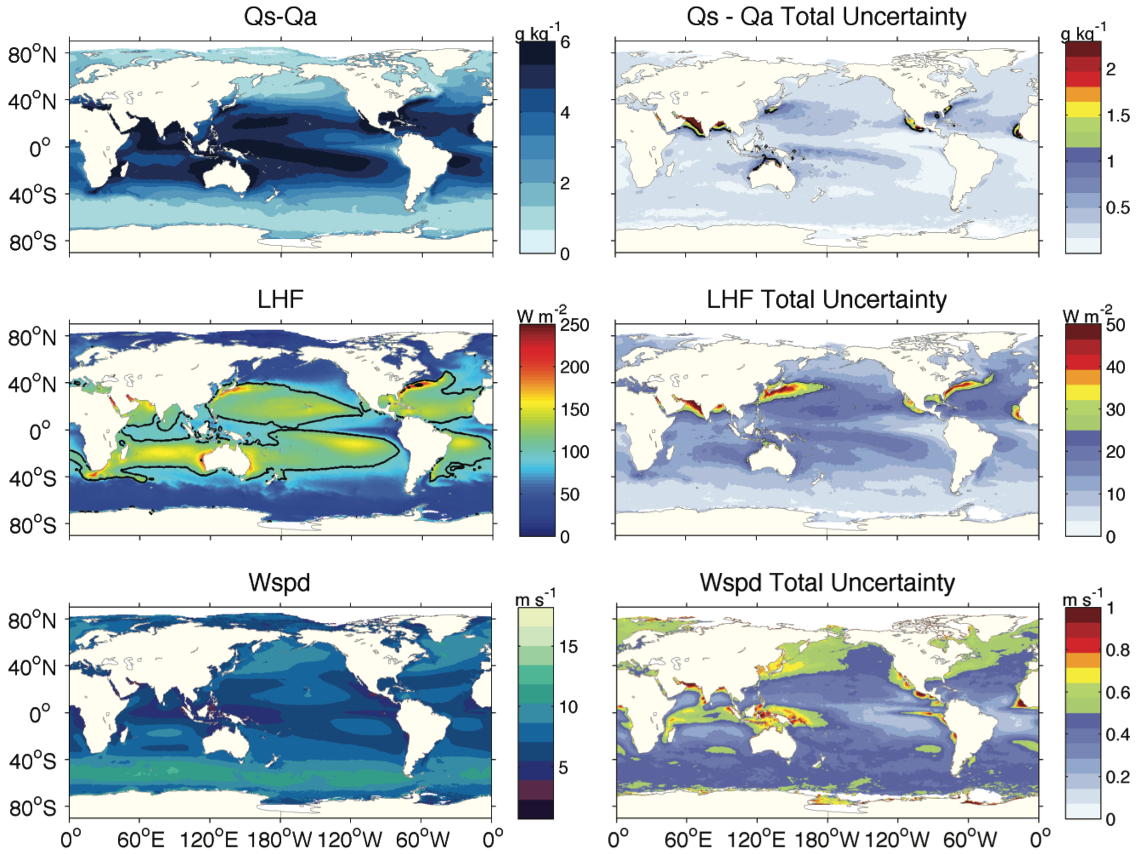
- Scatterometer winds
- Sea surface salinity
- Loss of passive microwave radiometers (SSM/I, SSMIS-type)
  - other communities, particularly sea-ice, are also extremely concerned about upcoming passive microwave gap

Current air-sea satellite heat flux products

	Spatial resolution	Highest temporal resolution	Period of availability
IFREMER	0.25°×0.25°	Daily	1992 – 2012
HOAPS	0.5°×0.5°	6-hourly	1987 - 2008
OAFLux	1°×1°	Daily	1985 - 2017
SEAFLUX CDR	0.25°×0.25°	3-hourly	1988 - 2017
J-OFURO	0.25°×0.25°	Daily	1988 - 2008

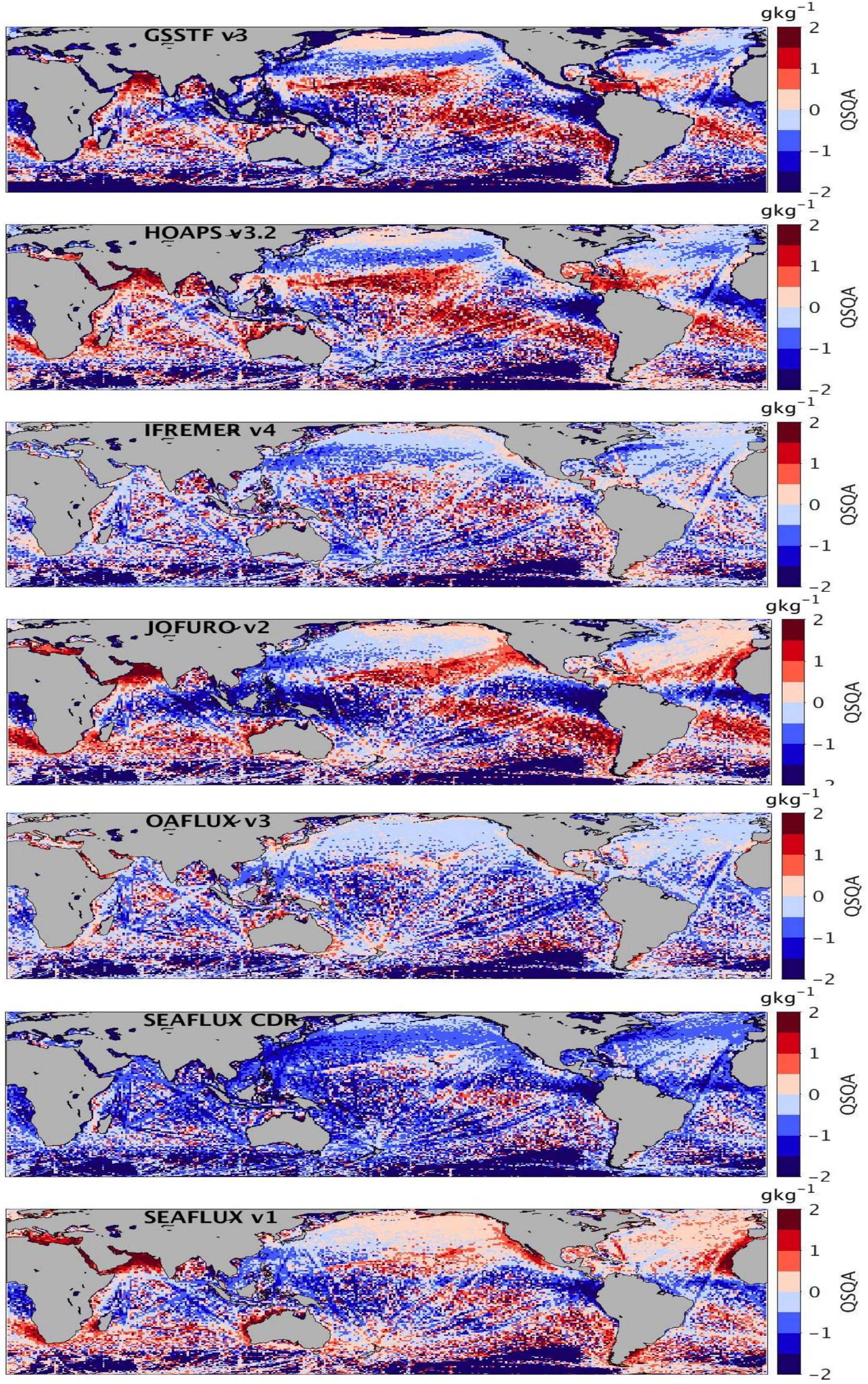
Errors in air-sea heat, moisture fluxes

- Largest errors appear to be coming from errors in atmospheric humidity (Qa) and temperature (Ta)
- Uncertainty estimate from SeaFlux (v1), 10-year means, for example:

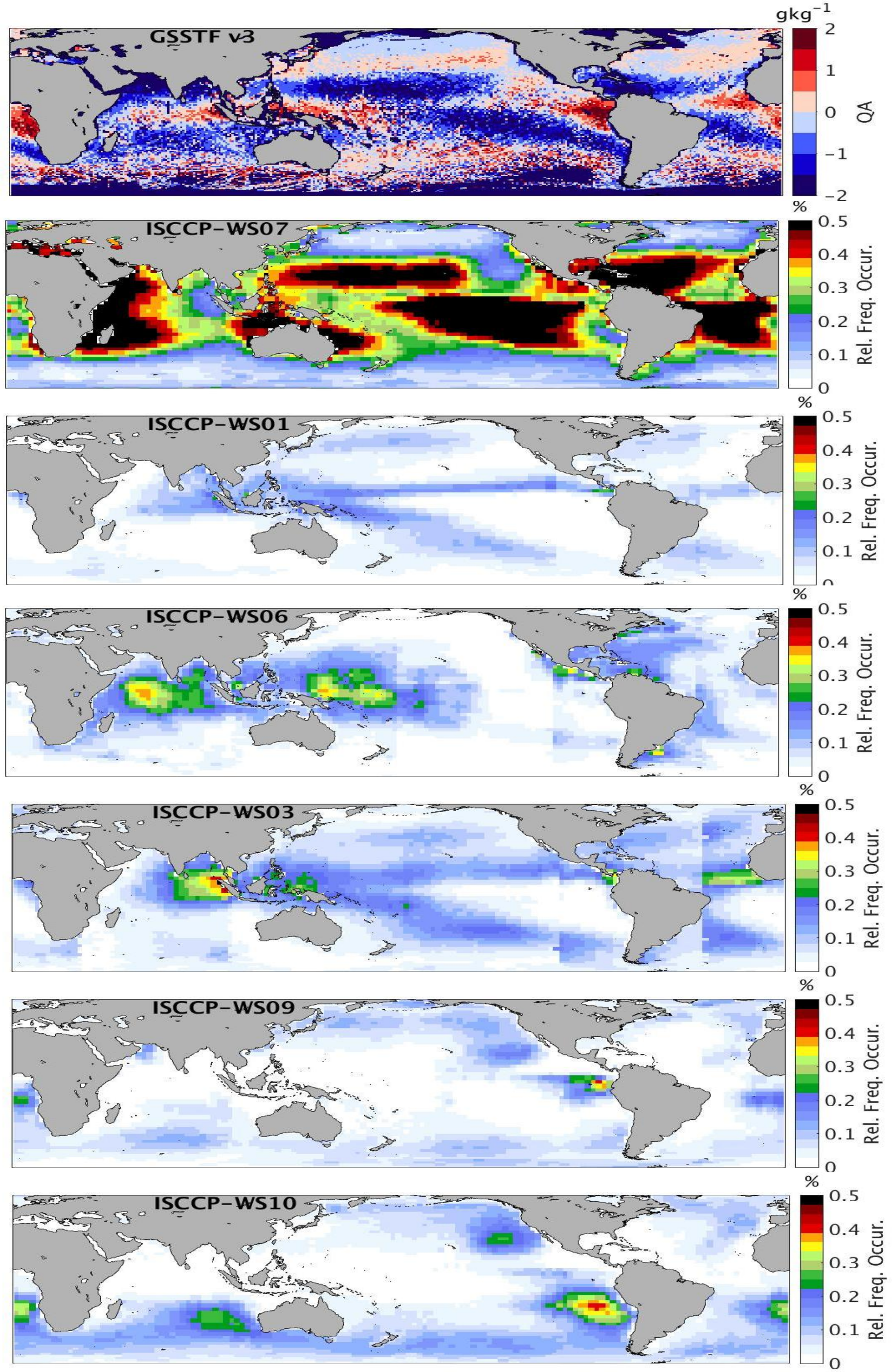


Variable	Global uncertainty
LHF (W m^{-2})	8.2 (9%)
SHF (W m^{-2})	4.2 (24%)
Windspeed (m s^{-1})	0.39 (5.2%)
Qa (g kg^{-1})	0.45 (4.0%)
SST (°C)	0.12 (< 1%)
Ta (°C)	0.35 (2%)
Ts - Ta (°C)	0.44 (33%)
Qs - Qa (g kg^{-1})	0.27 (8.2%)

Regional biases (Q_S-Q_A)



- The different products show strong regional patterns of biases in relation to surface observations (IVAD)
- Q_S-Q_A biases are driven primarily by differences in ***the near-surface humidity retrievals*** rather than ***SST (***true also of Ts – Ta, not shown)
- GSSTF v3, HOAPS v2, and JOFURO v2 all show a similar large scale pattern of biases, with strong regional signatures over the subtropical trade wind regimes and West Pacific STCZ
- IFREMER v4 and SeaFlux-V1 show muted regional signature, but they are still evident



Retrieval Biases and Cloud Weather States

- The structure in the retrieval (Qa, top) biases appear to be co-aligned with patterns of cloud weather states
  - WS are defined using ISCCP cloud-top histograms
- The largest biases in several of the Qa retrievals are aligned best with Global WS 7 (Tselioudis et al. 2012)
  - Mostly clear, w/ thin boundary layer cloudy
- **We can demonstrate improved results using a cloud-aware retrieval algorithm!**

Satellite air-sea turbulent fluxes – long records

There are multiple challenges at present for the development of accurate, precise, and consistent climate data records of turbulent latent and sensible heat fluxes (at the same time, significant progress has been made in the last ten years).

- Large **conditional/regional biases** affect current remote sensing based estimates of near-surface air temperature and humidity, particularly under different cloud regimes
- **Changes in the passive microwave observing system can generate anomalous variability** in estimated turbulent fluxes and may contribute substantially to inter-product differences prior to the mid-1990's.
- **New advances** are being made to address the development of climate-quality turbulent fluxes from remote sensing, including:
  1. Data Fusion
  2. New sensor development: with a focus on the ***atmospheric boundary layer***
  3. New approaches to handling **cloud impacts** on microwave brightness temperatures
  4. Improved **sampling and analysis/blending** techniques

- **What can CLIVAR advocate?** Beyond improvements of satellites for components (as seen in previous slides), *CLIVAR could advocate that* ***more resources could be allocated to evaluation, error uncertainty, and improvement of existing data sets****. CLIVAR could also advocate that we need* ***satellites with high vertical resolution in the atmospheric boundary layer.***

Surface freshwater flux: **precipitation**

- Global Precipitation Climatology Project (GPCP):
  - Derived primarily from SSMI/SSMIS series of satellites (passive microwave)
  - These satellites are dying and not being replaced (a pending gap in the system)
- Global Precipitation Mission (GPM) – US/JAXA mission

GPM precipitation: challenges + issues

Measurement challenges:

- Sensitivity to light rains and snow esp. in mid/high latitudes: budget not closed poleward of 55°
- Precipitation over steep topography

Potential gaps

- Launches planned in coming decade are insufficient to maintain the current international constellation of passive microwave satellites.
    - Potential offset: keep the legacy satellites flying for their entire useful life, e.g. MetOp-A now planned to be kept in orbit even after station-keeping fuel exhausted
- New, small satellites are being developed as technology improves, leading to the potential for better space/time coverage
    - But must meet the requirements (channels, coverage, resolution) of the precipitation community
- Process understanding: GPM is a single snapshot
    - Would be helped with a second radar pair/triplet, or Doppler capabilities

Surface freshwater flux: **sea surface salinity**

Two missions currently flying: SMOS (Europe) and SMAP (NASA).

<u>SMOS</u>

- Long time series (since 2009); mission hoped to be extended past 2019 (to 2021?)
- High spatial resolution (40 km), but accuracy/noise problems

<u>SMAP (Soil Moisture Active Passive):</u>

- Designed primarily for soil moisture but doing a great job with salinity (despite failure of wind sensor)
- 40 km resolution; accuracy nearly as good as that of Aquarius

<u>Aquarius (mission ended June 2015):</u>

- Versions 4 and 5 (final version) will have uncertainty estimates (both measurement and statistical errors)
- Continuous Aquarius-SMAP dataset may be produced: 2011-present time series for interannual studies

Sea surface salinity: issues and gaps

- No follow-on mission to Aquarius or SMAP currently planned – will leave a gap in the observing system.
- Current missions have low accuracy at high latitudes.
- Response to Decadal Survey RFI 1 and 2 submitted: advocates a dual band (L- and P-band) radiometer and L-band radar to capture salinity and sea ice thickness.
- Using SSS to constrain the freshwater flux budget is still an active science question.

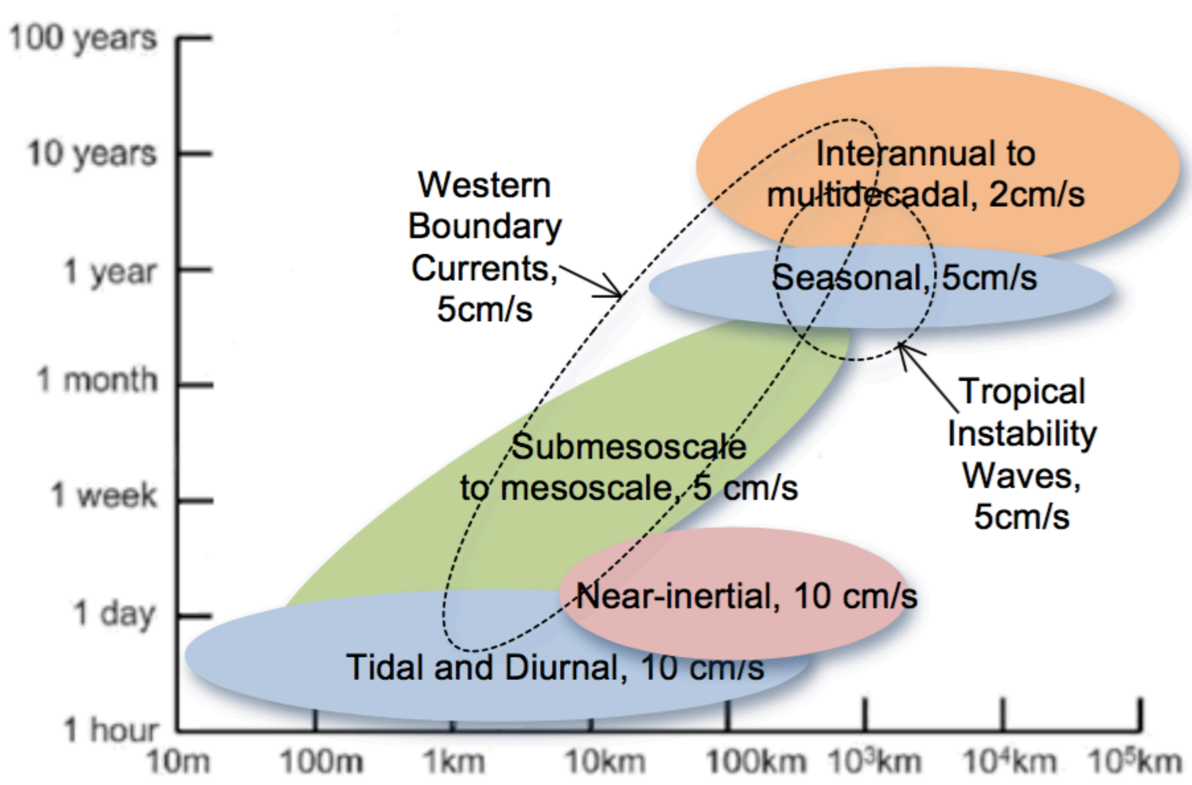
Momentum flux: **surface currents**

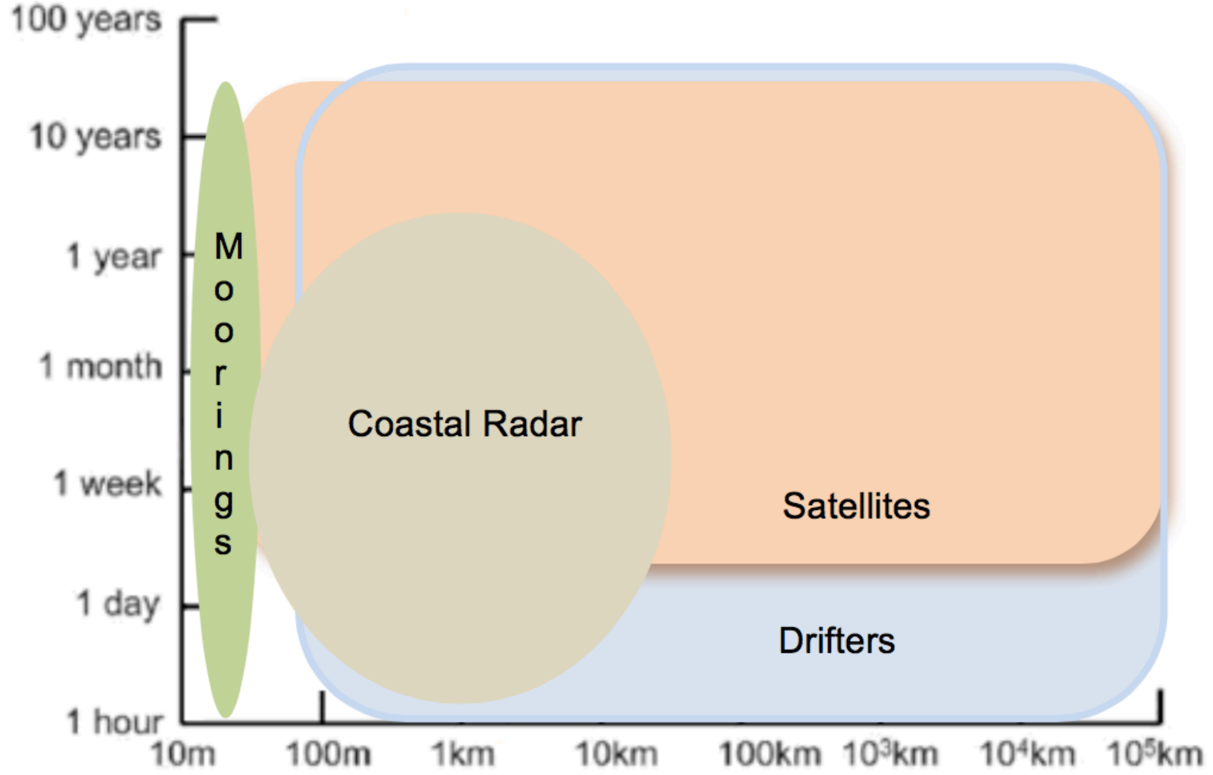
Importance to air-sea interaction from weather to climate:

- Wind stress & heat flux parameterizations depend on relative surface wind/ current speeds
  - Important in western boundary currents and ACC, at the mesoscale
- (Sub)mesoscale features are related to vertical currents and exchanges
- Surface currents affect wave steepness

Input from Kathleen Dohan – "Surface Currents Specification" document from the Oceans Observing Panel for Climate

(Near)-surface currents





* “Surface Currents Specification” document from the Oceans Observing Panel for Climate

(Near)-surface currents

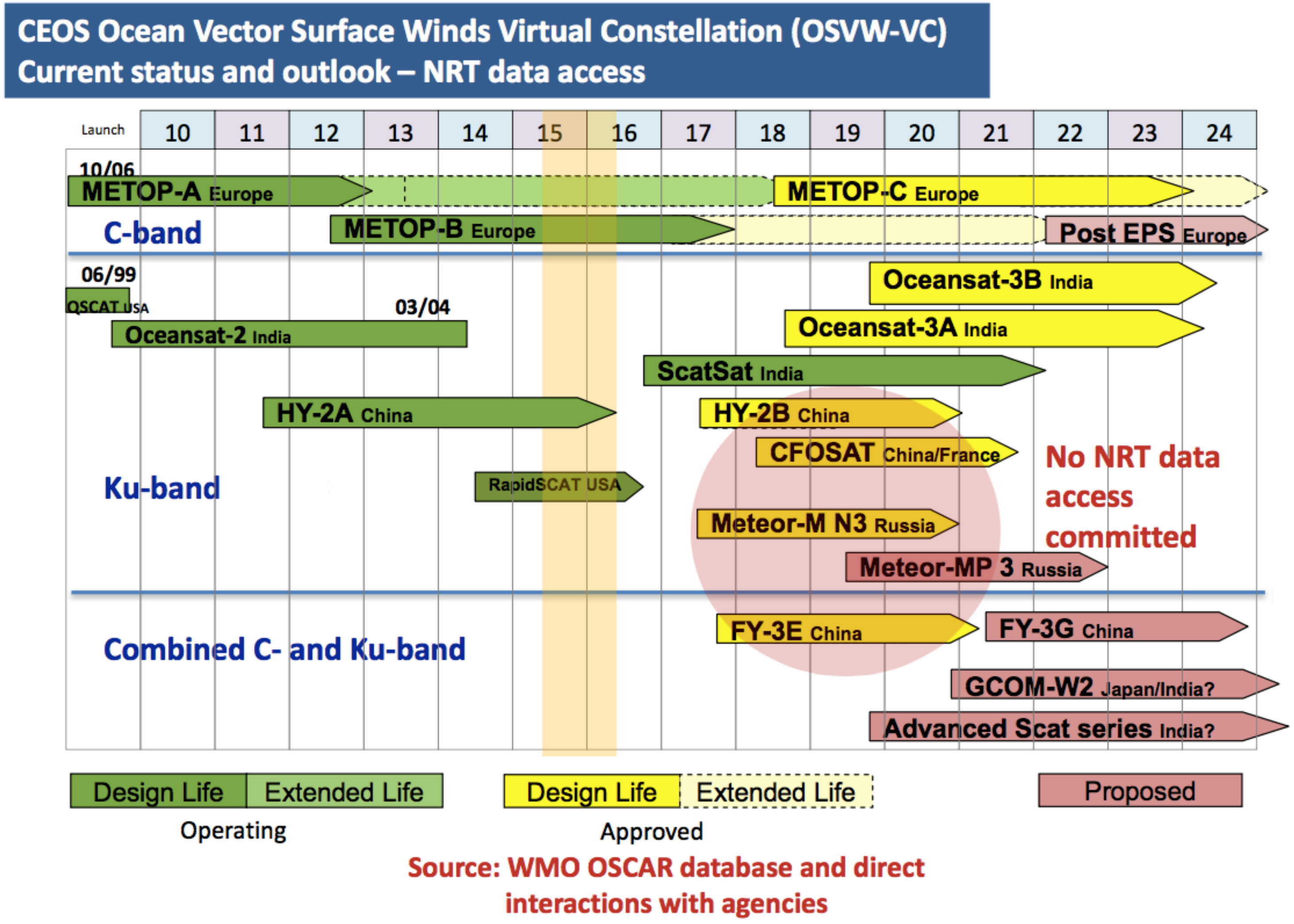
Satellite-derived products:

- Use altimetric sea level anomaly (± vector winds for Ekman component, surface drifters)
- Capture intraseasonal–multidecadal, 25-km to global scales
- E.g. AVISO (altimetry only), OSCAR (1/3°, 5-day), SCUD (1/4°, daily)
- ~ 10 cm/s random uncertainty

Gaps in the observing system:

- Smaller-/faster-scale processes (SWOT may help this)
- Spatial derivatives in both horizontal dimensions are not resolved with the existing observing system.
- Meridional current measurements at the equator are not sufficiently accurate to determine the magnitude of equatorial upwelling

Surface momentum flux: **wind vectors**



- Few gaps since 1991
- Backbone of the constellation is European (METOP) and Indian (ScatSAT, Oceansat)
- Currently, no US scatterometer flying
- Ku-band and C-band have different qualities

* https://mdc.coaps.fsu.edu/scatterometry/meeting/past.php#2017 – Paul Chang presentation

Scatterometer uncertainties

- Largest source of uncertainties appears to be that we keep tuning scatterometers to wind ***speeds/vectors***
  - Scatterometers are most closely measuring equivalent neutral winds or stress
  - Stress is most closely related to neutral wind speed measured relative to the ocean surface
- Currently we then take the scatterometer measurement, convert it to a wind speed/vector
  - Requires knowing atmospheric stability (which is much more uncertain than the stress measurement), and the surface currents, and use of a PBL model
- And then we take the wind information, use a model (again!) and convert to stress

Scatterometer uncertainties (potential solution)

- If future scatterometers are tuned to equivalent neutral winds or stress, then the uncertainty of relating the wind speed to the momentum flux is *substantially* eliminated

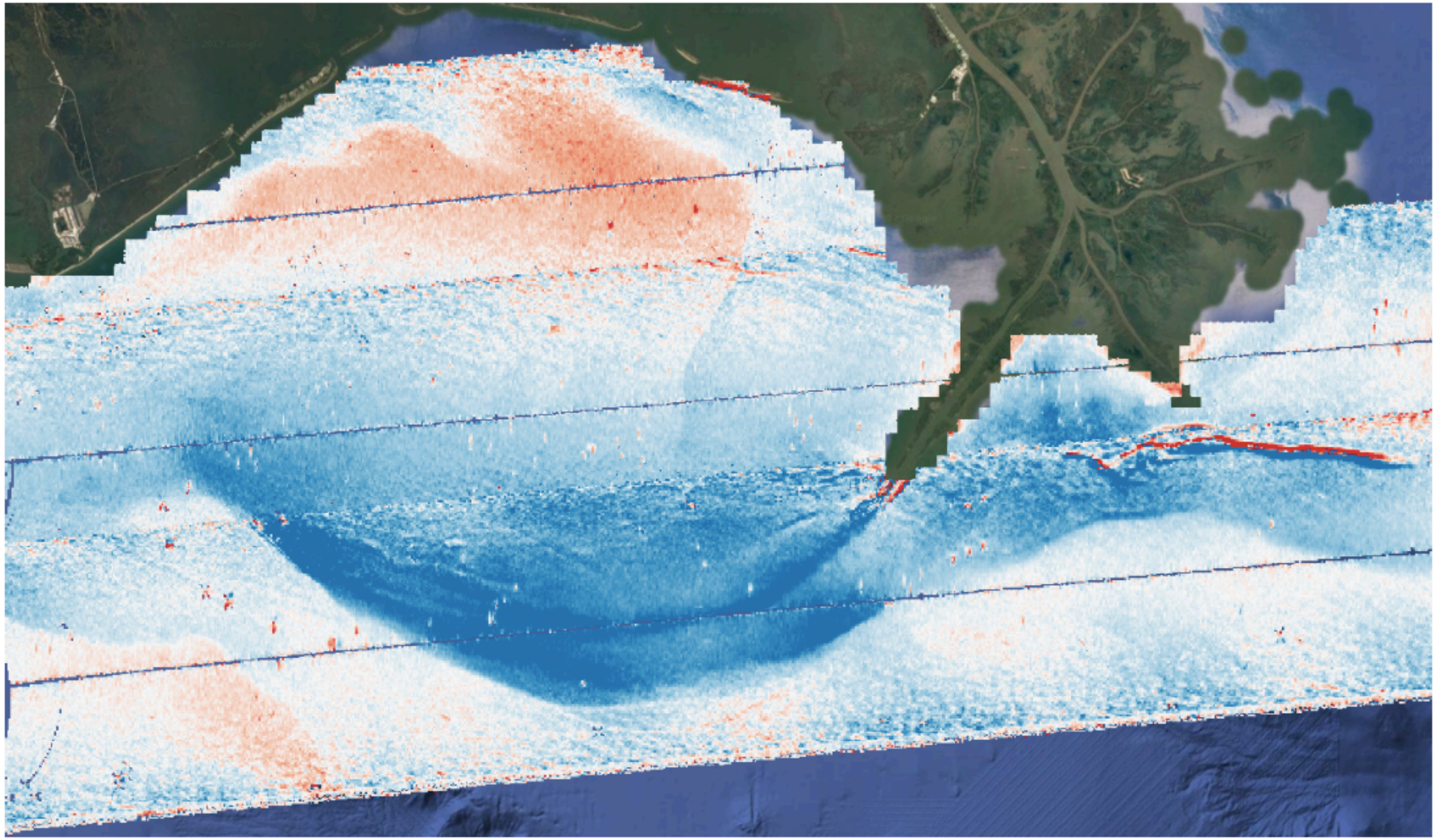
- US CLIVAR could recommend tuning future scatterometers to equivalent neutral winds or stress

- US CLIVAR could also recommend that a careful analysis of the uncertainties in the scatterometer winds from previously related issues be undertaken, so that the community could be aware of where the biggest “bang for the buck” in improving the errors would come from

Next-generation? Doppler scatterometer that measures winds and currents simultaneously

- Motivation:
  - Winds and currents are tightly coupled Essential Climate Variables
  - Winds drive horizontal and vertical ocean circulation; currents provide a moving reference frame for winds
  - Simultaneous wind/current measurements would benefit oceanography and meteorology
- DopplerScatt: NASA’s proof-of-concept mission (airborne)

DopplerScatt U Surface Velocity



https://mdc.coaps.fsu.edu/scatterometry/meeting/docs/2017/docs/Wednesday/morning/SecondSession/

Winds and Current Mission (WaCM): satellite version of DopplerScatt

- 5-km horizontal resolution:
  - Will capture submesoscale/mesoscale transition, near-coastal winds
  - Highly sensitive to rain
- Recommendation made for decadal survey by multiple RF1 and RF2 responses
- US CLIVAR could advocate a scatterometer and/or a Doppler scatterometer

COWVR: Compact Ocean Wind Vector Radiometer

- Made for JPL; to be launched in late 2017
- Two-look polarimetric (2LP) microwave radiometer, full 360^{o} view, 18 channels
- *Internal* calibration: means improved cost effectiveness: constellation possible with increased temporal coverage
- 2LP radiometers do not require an ancillary wind field for ambiguity removal for winds above 6-7 m/s; two-look system in theory better for low and moderate wind speeds, near rain, and reduced noise in vectors → better convergence/divergence
- Can measure SST, near-surface ocean vector winds and sea-surface wind stress; total water vapor and cloud water in the atmosphere; precipitation, sea-ice extent, concentration, and age, snow cover over land
- Recommendation made for decadal survey by multiple RF1 and RF2 responses

- **Not sure what US CLIVAR could advocate for here, as a test is going up, but we should at least be supportive of this approach, which has some real advantages**

Satellite wind *speeds*

- Some air-sea interaction calculations depend on wind speed rather than vector winds
- Satellite coverage of wind speeds is good, since passive microwave sensors measure wind speeds (e.g., SSM/I, SSMIS, Aquarius): but, there is an upcoming gap when SSMIS are over
- CYGNSS: new high-wind-speed mission for understanding tropical cyclones; however, significant technological challenges remain for this
- Interleaving wind speed and vector wind measurements for maximum effect is an open challenge

Sea Surface Temperature

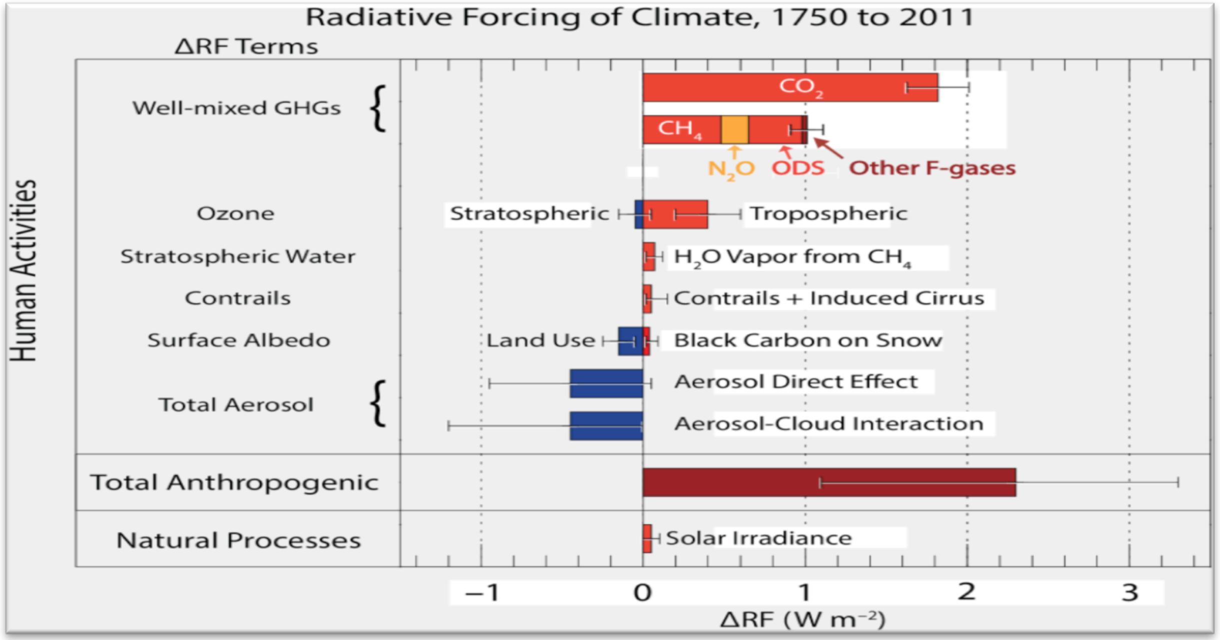
- The state of satellite SST observations is healthy!
- NOAA maintains numerous AVHRR instruments (European partnership), which have 1-km resolution (infrared – cloud-free data only)
- NASA has several infrared satellites with 1 to 4-km resolution (MODIS, VIIRS, Aqua, Terra)
- AMSR-2 provides microwave SSTs (works in cloudy conditions)
- Numerous optimally-interpolated products blending IR/microwave data
- **Gaps: adequate resolution to fully capture the diurnal cycle; still convincing the community that some applications need skin, not "foundation" temperature**

Information about the data is as important as the data itself (almost!) What kinds of information? And why does it matter?

- Uncertainty of data: describes doubt we have about the quantity we are measuring, given the result of a measurement and our estimate of the error distribution
- Quality of data: complementary information
  - Confidence in uncertainty estimate
  - Conditions violating retrieval or measurement assumptions
- Additional uses of uncertainty:
  - Data assimilation
  - Comparison of data/models

The use of uncertainty for determination of future missions (thoughts from the Decadal Survey)

- What are greatest science needs? One argument: where uncertainty is highest. IPCC/atmospheric community does a great job at outlining uncertainty



After Fig. 8.15 of IPCC (2013)

- Need uncertainty targets: set *quantifiable* goals: it's no longer enough to use phrases like "understand better"

Thoughts on best practices

- Include **quantitative uncertainty** information with dataset at each data point (not just in some paper with overall error analysis)
- Use **propagation of errors** when combining data
- **Quality flags** shouldn't be used to pass judgment based on uncertainty, but can be used to provide information about how well the uncertainty is known
- **Documentation** should include information on uncertainty, how it was calculated, how it it varies across time/space scales
- **Validation** should be of both data and uncertainty estimates
- There are a number of ways to calculate uncertainty, and even some uncertainty about what uncertainty is: **as a community we need to get a handle on this, and start requiring some estimates when producing data sets**