NOAA Aerosols and Ocean Science Expeditions (AEROSE): Ocean-Based Campaigns Supporting NOAA Satellite Remote Sensing

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Acknowledgments

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  - NOAA AEROSE
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    - NOAA Educational Partnership Program (EPP) grant NA17AE1625, NOAA grant NA17AE1623
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    - D. Holdridge and J. Mather (ARM Climate Research Facility)
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  - MAERI: P. J. Minnett, M. Szczodrak, M. Izaguirre (UM/RSMAS)
  - Howard University Beltsville: R. Sakai, B. Demoz, M. Oyola (HU/NCAS)

Outline

- Satellite Calibration/Validation (Cal/Val) Overview
  - Satellite Remote Sensing
  - Satellite Cal/Val

- AEROSE Data and Science Overview
  - Campaign Overview
  - Meteorological Phenomena of Interest
  - Data of Interest

- AEROSE Science Highlights
  - Environmental Data Record (EDR) Validation
    - Temperature (T) and Water Vapor (H₂O) profiles
      - SNPP NUCAPS Global Statistical Performance Characterization
      - Aerosol Impact on Retrievals
      - GOES-R ABI Legacy T / H₂O
      - Cloud/Aerosol Cloud-Cleared Radiance Contamination
    - SNPP IR Ozone (O₃) profiles
    - Using EDRs as Observations
      - Saharan Air Layers (SAL) and Hadley Cells
      - Atmospheric Rivers (ARs)
    - IR Emissivity Model Development and Validation
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SATELLITE CALIBRATION/VALIDATION (CAL/VAL) OVERVIEW
Remote Sensing vs. In Situ Sensing

- A measurement is considered in situ (Latin for “in place”) when the sensor is in direct material contact with the medium being measured
  - Example sensors: thermometer, anemometer, hygrometer, tongue, nose
  - Example observing systems: RAOB, met station, buoy, CTD, XBT

- A remotely sensed measurement, on the other hand, is, strictly speaking, one that is obtained through electromagnetic (EM) radiative transfer. EM radiation propagates through empty space, and thus a measurement is obtained “remotely,” i.e., not in direct contact.
  - Example sensors: radiometer, spectrometer, Radar, Lidar, telescope, microscope, eye
  - Example observing systems: Satellite based (downlooking), surface based (uplooking)
Satellite Measurements Provide Global Data

Environmental Satellite Constellation

- **Raw Data Records (RDRs)**
- **Sensor Data Records (SDRs)**
  - Calibrated, geo-located spectral radiances
  - Infrared (IR)
  - Microwave (MW)
  - Solar/Optical (VIS)
  - Active (e.g., lidar, radar)
  - Passive (e.g., radiometer, spectrometer)

- **Environmental Data Records (EDRs)**
  - Retrievals via inversion
  - Soundings (temperature, moisture, trace gas)
  - Sea surface temperature, salinity, height, ocean color
  - Aerosols (dust, smoke)
  - Clouds
  - Radiation budget
Operational Environmental Satellite Passive Sensor System Example: Suomi NPP (SNPP) CrIS/ATMS Sounder System

SNPP Satellite
- CrIS IR spectrometer
- ATMS MW radiometer

SDR/EDR products derived from 3x3 Array of CrIS FOVs (each at 14-km Diameter) matched to ATMS footprint

Central or Regional Ground Stations

RDR = Raw Data Record
(e.g. CrIS Interferograms)

SDR = Sensor Data Record
(e.g. Calibrated IR Spectra)

EDR = Environmental Data Record
(e.g. Atmospheric Temperature and Moisture Profiles)

Courtesy of Chris Barnet (STC, Inc.)
NOAA Unique Combined Atmospheric Processing System (NUCAPS) Algorithm

- **Operational algorithm**
  - NOAA Enterprise Algorithm for CrIS/IASI/AIRS (Susskind, Barnet and Blaisdell, IEEE 2003; Gambacorta et al., 2014)
  - Global non-precipitating conditions
  - Atmospheric Vertical Temperature, Moisture Profiles (AVTP, AVMP)
  - Trace gases (O₃, CO, CO₂, CH₄)

- **Users**
  - Weather Forecast Offices (AWIPS)
    - Nowcasting / severe weather
    - Alaska (cold core)
  - NOAA/CPC (OLR)
  - NOAA/ARL (IR ozone, trace gases)
  - NOAA TOAST product (IR ozone)
  - Basic and applied science research (e.g., Pagano et al., 2014)
    - Via NOAA Data Centers (e.g., CLASS)
    - Universities, peer-reviewed pubs

15 May 2017

Dr. Nick Nalli - ESSIC Seminar
Calibration/Validation (Cal/Val)

- **Validation** is “the process of ascribing uncertainties to... radiances and retrieved quantities through comparison with correlative observations” (Fetzer et al., 2003)
  - “Correlative observations” refers to an independent measurement (*in situ* or remotely sensed) used as a **baseline** or “**truth**”
- EDR cal/val supports monitoring of SDRs and cloud-cleared radiances
- EDR cal/val enables development/improvement of algorithms
NOAA Validation Datasets and Tools

• **STAR Validation Archive (VALAR)**
  - Dedicated/reference and intensive campaign RAOBs
  - SDR/TDR granule-based collocations within 500 km radius acquired off SCDR (past 90 days) or CLASS (older than 90 days)
  - Trace Gas and O₃ EDR validation
  - Rigorous coarse-layer (1-km, 2-km) product performance measures based on statistical metrics corresponding to Level 1 Requirements detailed in *Nalli et al.* (2013)

• **NOAA Products Validation System (NPROVS) (*Reale et al.*, 2012)**
  - Performs global RAOB collocations for multiple satellite platforms
    - Conventional WMO RAOBs
    - Dedicated/reference (NPROVS+) (*Sun et al.* 2017)
  - HDF5-formatted Collocation Files facilitates GRUAN RAOB matchups within VALAR
  - NRT monitoring capability
  - Satellite EDR intercomparison capability
  - Java based graphical user interface tools for monitoring (PDISP, NARCS, ODS)
IR Sounder Validation Methodology Hierarchy
(e.g., Nalli et al., JGR Special Section, 2013)

1. Numerical Model (e.g., ECMWF, NCEP/GFS) Global Comparisons
   - Large, truly global samples acquired from Focus Days
   - Useful for sanity checks, bias tuning and regression
   - Limitation: Not independent truth data

2. Satellite Sounder EDR (e.g., AIRS, ATOVS, COSMIC) Intercomparisons
   - Global samples acquired from Focus Days (e.g., AIRS)
   - Consistency checks; merits of different retrieval algorithms
   - Limitation: Similar error characteristics; must take rigorous account of averaging kernels of both systems (e.g., Rodgers and Connor, 2003)

3. Conventional RAOB Matchup Assessments
   - WMO/GTS operational sondes launched ~2/day for NWP
   - Representation of global zones, long-term monitoring
   - Large samples after a couple months (e.g., Divakarla et al., 2006; Reale et al. 2012)
   - Limitations:
     - Skewed distribution toward NH-continents
     - Mismatch errors, potentially systematic at individual sites
     - Non-uniform, less-accurate radiosondes
     - RAOBs assimilated into numerical models

4. Dedicated/Reference RAOB Matchup Assessments
   - Dedicated for the purpose of satellite validation
     - Known measurement uncertainty, optimal accuracy
     - Minimal mismatch errors
     - "best estimates" or "merged soundings"
   - Reference sondes: CFH, GRUAN corrected RS92/RS41
     - Traceable measurement
     - Uncertainty estimates
   - Limitation: Small sample sizes, geographic coverage
   - E.g., ARM sites (e.g., Tobin et al., 2006), AEROSE, CalWater/ACAPEX, BCCSO, PMRF

5. Intensive Field Campaign Dissections
   - Include dedicated RAOBs, some not assimilated into NWP models
   - Include ancillary datasets (e.g., ozonesondes, lidar, M-AERI, MWR, sunphotometer, etc.)
   - Ideally include funded aircraft campaign using IR sounder (e.g., NAST-I, S-HIS)
   - Detailed performance specification; state specification; SDR cal/val; case studies
   - E.g., SNAP, SNPP-1,-2, AEROSE, CalWater/ACAPEX, JAIVEX, WAVES, AWEX-G, EAQUATE
NOAA Aerosols and Ocean Science Expeditions (AEROSE): Ocean-Based Campaigns Supporting NOAA Satellite Remote Sensing

AEROSE DATA AND SCIENCE OVERVIEW
AEROSE Campaigns

• NOAA/NCAS Aerosols and Ocean Science Expeditions (AEROSE)
  – Collaborative ship-based trans-Atlantic intensive field campaigns (Morris et al. 2006; Nalli et al. 2011)
  – Recent campaigns (conducted since the launch of SNPP satellite)
    ß 2013a (NOAA Ship Ronald H. Brown, Jan-Feb 2013; 38 days)
    ß 2013b (NOAAS Ronald H. Brown, Nov-Dec 2013; 30 days)
    ß 2015 CalWater ARM Cloud, Aerosol and Precipitation Experiment (ACAPEX)
      ○ In Jan-Feb 2015, AEROSE collaborated in the CalWater/ACAPEX campaign (NOAA Ship Ronald H. Brown, Pacific Ocean, 30 days)
    ß 2015 (NRV Alliance, Nov-Dec 2015; 30 days)
    ß 2017 (NOAAS Ronald H. Brown, Feb-Mar 2017; 37 days)

• AEROSE has yielded an unprecedented collection of in situ measurements
  – Saharan air layer (SAL) and associated African dust and smoke outflows over the tropical Atlantic Ocean
  – Pacific Ocean atmospheric rivers (ARs) off coast of California
  – Important for satellite sounder validation because sounders are meant to provide information under “challenging” weather conditions
  – Ocean-based dedicated RAOBs form an important component of the overall JPSS Intensive Cal/Val (ICV) effort (Nalli et al. 2011, 2013; Xie et al. 2013)
Ocean-Based Intensive Field Campaigns

• Unique Advantages
  – Earth’s surface is ≈70% ocean
  – Oceans drive climate and weather
  – Satellite data makes biggest impact over oceans given paucity of data
  – Ocean surface is radiatively uniform, well-understood and easier to specify than land surfaces

• Campaigns of Note
  – 1995 OTIS Cruise
    β LUMCON RV Pelican
    β Gulf of Mexico
    β First IR surface spectra
  – 1997 Combined Sensor Program
    β NOAA Ship Discoverer
    β Tropical Western Pacific Ocean
    β First MAERI prototype
  – AEROSE 2004–present
    β NOAA Ship Ronald H. Brown
    β NATO RV Alliance
    β Tropical Atlantic Ocean
  – CalWater/ACAPEX 2015
    β Jan-Feb 2015, NOAA Ship Ronald H. Brown
    β Central Pacific Ocean
AEROSE Partnerships

• Participating Institutions
  – Howard University NOAA Center for Atmospheric Sciences (HU/NCAS)
  – NOAA/NESDIS/STAR
  – University of Miami/RSMAS
  – NOAA/ESRL/PSD
  – NOAA/OAR Atlantic Oceanographic and Meteorological Laboratory (AOML)
  – NOAA Pacific Marine Environmental Laboratory (PMEL)
  – DOE Atmospheric Radiation Measurement (ARM) Program
  – STC, Inc.

• Synergism
  – Low Cost – Low Risk
  – Engages broader science community on specific problems
  – All parties gain access to all data

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<tr>
<th>AEROSE EDR Cal/Val Contributors</th>
<th>INSTITUTION</th>
<th>COLLABORATION</th>
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<tbody>
<tr>
<td>NAME</td>
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<tr>
<td>R. Lumpkin, C. Schmid, R. Perez, G. Foltz,</td>
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<td>PNE Chief Scientists TAO Moorings CTDs, XBTs</td>
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<td>M-AERI MW Radiometer All-sky camera</td>
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<td>D. Wolfe et al.</td>
<td>NOAA/OAR/ ESRL/PSD</td>
<td>Vaisala Sounding System; Surface Flux Measurements; Vaisala Ceilometer</td>
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Science goals of AEROSE include (Morris et al. 2006; Nalli et al. 2006, 2011)

1. Observation of dust and smoke aerosol distributions during trans-Atlantic transport, including physical and chemical evolution over space and time.

2. Observation of Saharan and sub-Saharan outflows and their impact upon the regional atmosphere and ocean during trans-Atlantic transport.

3. Assessment of satellite products and numerical models for resolving and studying the above processes.
AEROSE Featured in BAMS

- A comprehensive overview paper describing AEROSE (Nalli et al., 2011) was published as a Science Article in the June 2011 issue of the Bulletin of the American Meteorological Society (BAMS)
- The AEROSE paper got the cover photo and headline
- Science topics of interest are highlighted, with emphasis given to satellite cal/val (JPSS, IASI and GOES-R)
Dust and Smoke Aerosol Outflows

- **~100–400 Tg of mineral dust** are injected into the atmosphere from the Sahara annually (Prospero et al. 1981).
  - Peaks during NH summer and springtime
  - Coarse-mode aerosols, often transported within easterly trade winds well across the Atlantic north of the ITCZ
  - Westward flow accounts for the 30–50% of the dust output
  - Most readily detected by satellite sensors

- **Smoke from biomass burning** from sub-Saharan Africa also contribute large quantities of smaller-sized aerosols

- These have a significant impact on the chemistry, meteorology and climate dynamics of the tropical North Atlantic (e.g., radiation balance)

- Due to absorption/scattering, they also impact infrared radiances, and thus geophysical retrievals (e.g., Nalli and Stowe 2002; Weaver et al. 2003)
Dust Outflow Event - 12-15 May 2007
Aerosol Impact on the Chemistry of the Tropical Atlantic Atmosphere

- Surface aerosol-gas reactions and transport
- Tropospheric ozone
  - Smoke aerosol precursors (CO) from African and South American biomass burning
    - Horizontal advection via easterlies
    - Vertical transport via tropical deep convection
  - Lightening in deep convection – NO\textsubscript{x} precursor formation
  - Stratospheric intrusions
Moisture Transport: Saharan Air Layers and Hadley Cells

- **Saharan Air Layers (SAL)**
  - Synoptic to mesoscale stable layers of dry, warm air of desert origin
  - Advect across the Atlantic Ocean, often accompanying high levels of Saharan dust aerosols (Carlson and Prospero 1972).
  - These stabilizing conditions may suppress hurricane activity over the Atlantic (e.g., Karyampudi and Pierce 2002; Dunion and Velden 2004; Wong and Dessler 2005; Evan et al. 2006; Sun et al. 2008; Shu and Wu 2009), and may also be self-sustaining as a result of reduced radiative cooling in the layer.

- **Hadley Cells**
  - Global/synoptic scale circulation cells consisting of uplift along the ITCZ axis and associated poleward divergence aloft
  - Subtropical subsidence causes drying and warming, leading to deep columns of dry air with stabilizing tropospheric inversions at their bases (“advection-condensation model”; Pierrehumbert et al. 2007)
Moisture Transport: Atmospheric Rivers (ARs)

- **Atmospheric Rivers (ARs)** are narrow channels of moisture transport that are associated with midlatitude storm systems and that can extend thousands of km offshore (e.g., Dettinger et al. 2015; Dacre et al. 2015; Ramos et al. 2016)
  - Important for forecasting coastal precipitation (e.g., the West Coast)
  - “Drought busters” (Dettinger 2013) after the record 2012–2015 California drought (e.g., Swain 2015)
- Understanding of ARs is important for forecasting West Coast precipitation, and given California droughts of recent years, ARs are a hot topic of current research
- **Satellite sensors** are tools whereby both SAL and AR phenomena can be observed synoptically; this is another reason why validation in these regions is highly desirable

Figure 1. Conceptual framework for CalWater 2 science goals. The proposed observational strategy includes airborne and ship-based assets over the central and eastern Pacific complemented by ground-based measurements along the U.S. West Coast.
2015 CalWater/ACAPEX Campaign

• California’s water (CalWater) is influenced by extreme precipitation events associated with
  – Atmospheric Rivers (ARs)
  – Aerosols from local and remote sources

• CalWater 2015 was a multi-institutional intensive field campaign to obtain a suite of observations for gaining understanding of these phenomena
  – Aircraft-based data
    ☐ NOAA P-3
    ☐ NOAA G-IV
    ☐ DOE G-1
    ☐ NASA ER-2
  – Land-based networks
    ☐ NOAA Hydrometeorology Testbed (HMT) mesonet sites
  – ACAPEX/AEROSE sub-campaign, NOAA Ronald H. Brown, AMF2
    ☐ Leg 1: Honolulu to San Francisco
    ☐ Leg 2: San Francisco to San Diego
Data (1/5): *In situ* Gas & Particle Measurements

- **TECO (Thermo Electron Corp.) Measurements**
  - Ozone Photometer: Ambient gas-phase $O_3$
  - CO IR Spectrometer: Ambient gas-phase CO
  - $NO_x$ Chemiluminescence Analyzer: Ambient NO + NO$_2$
  - SO$_2$ Fluorometer: Ambient gas-phase SO$_2$

- **Chemical and Bulk sampling**
  - Uses quartz and Teflon filters

- **Condensation Particle Counter**
  - Enlarges particles via condensation for easy counting

- **Laser Particle Counter**
  - Measures aerosol number density

- **QCM (Quartz Crystal Microbalance) Cascade Impactor**
  - Measures aerosol mass density
Data (2/5): Broadband Radiometer Fluxes

AEROSE Broadband SW and LW Downwelling Sfc Fluxes

- 2004 AEROSE-I
- 2006 PNE/AEROSE-II
- 2007 PNE/AEROSE-III
- 2008 RE.00.03 AEROSE-IV
- 2009 PNE/AEROSE-V
- 2010 PNE/AEROSE-VI
- 2011 PNE/AEROSE-VII
- 2013a PNE/AEROSE-VIII
- 2013b PNE/AEROSE-IX

Date (mm/dd)

25
AEROSE collaborates with the NASA GSFC Maritime Aerosol Network (MAN)

- The MAN calibration, measurement and QA methodology for Microtops handheld sunphotometers was applied to retrieve a standardized AOD
- AEROSE Microtops data are included in the MAN data archive (Smirnov et al. 2010)

Data (4/5): Marine Atmospheric Emitted Radiance Interferometer (MAERI)
(Minnett et al. 2002)

- **Ship-based FTS** that measures downwelling and upwelling calibrated IR spectra *(Minnett et al. 2001)*

- High accuracy calibration using 2 NIST-traceable blackbodies

- Derived (EDR) products
  - **High accuracy skin SST** derived from semi-opaque spectral region (~7.7 µm) *(Smith et al. 1996)*
    - **Skin SST** is an important state parameter and “ground truth”
  - Retrievals of lower tropospheric profiles at turbulent time scales *(e.g., Szczodrak et al. 2007)*
  - Ocean surface spectral emissivity *(e.g., Hanafin and Minnett 2005; Nalli et al. 2008b)*
Data (5/5): Dedicated Radiosonde Observations (RAOB): 

\(PTU, O_3\)

- **Vaisala RS92/RS41 GPS rawinsondes**
  - Launched coinciding LEO environmental satellite overpasses
    - Suomi NPP (CrIS/ATMS)
    - MetOp-A and -B (IASI)
    - Aqua, A-Train (AIRS)
  - Pressure, temperature, humidity, \(PTU(z)\), GPS winds and altitude
  - Not uploaded into GTS (i.e., not assimilated)
  - 1295 total ocean-based soundings acquired
    - 111 RS41 soundings in Feb-Mar 2017

- **ECC Ozonesondes** interfaced with RS92
  - Measure \(O_3(z)\) partial pressure
  - \(~1/\text{day} \) during SNPP overpasses
  - 195 full or partial \(O_3\) soundings to date
    - 13 \(O_3\) soundings in Feb-Mar 2017
2017 AEROSE Campaign (SNPP Year-5)

- The **2017 NOAA AEROSE** took place onboard the NOAA Ship *Ronald H. Brown*
  - 19 Feb to 25 Mar 2017
  - Montevideo, Uruguay to Charleston, SC
- **117 Vaisala RS41-SGP, RS41-SG and RS92-SGP** radiosondes launched
  - 111 full or partial soundings were obtained
  - Dedicated sondes were launched for SNPP and MetOp overpasses
    - These will provide another **fully independent truth dataset**
      - not assimilated
      - decoupled from land-based sites
    - These data will also automatically collocate with GOES-16 (GOES-R), thereby allowing “two for the price of one” validation opportunities
- **13 full or partial dedicated ozonesoundings** were obtained from ECC ozonesondes interfaced with Vaisala RS92-SGP rawinsondes
AEROSE-X (Dec 2015, NATO RV Alliance)
AEROSE SNPP-Dedicated Ozonesonde Launch (2/2)

AEROSE-X (Dec 2015, NATO RV Alliance)
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AEROSE SCIENCE HIGHLIGHTS
SNPP NUCAPS T/H$_2$O Global Validation
Dedicated/Reference RAOB-Retrieval Collocation Sample

JPSS SNPP-Dedicated and GRUAN Reference RAOB Sites

Geographic Histogram
FOR Collocation Criteria
δx ≤ 75 km, −60 < δt < 0 min
NUCAPS (v1.5 Nom-Res CrIS) AVTP Coarse-Layer Statistics
Dedicated/Reference RAOB Collocation Sample

AVTP Versus RAOB

** Broad-Layer Stats (Per JPSS Level 1 Requirements)

IR+MW
MW-Only

IR+MW Yield
= 63.3%

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NUCAPS (v1.5 Nom-Res CrIS) AVMP Coarse-Layer Statistics Dedicated/Reference RAOB Collocation Sample

AVMP Versus RAOB

Broad Layer Stats (Per JPSS Level 1 Requirements)

IR+MW
MW-Only

IR+MW Yield
= 63.3%
Aerosol Impact on IR Profile Retrievals
(Maddy et al. 2012)

Figures taken from Maddy et al. (2012)
GOES-R Pre-Launch Validation (Xie et al. 2013)

Figures taken from Xie et al. (2013)
Cloud/Aerosol Contamination in calc (LBL) – obs (CCR)

After Nalli et al. (2012, 2013)
• Collocated ozonesondes for $O_3$ (ozone) profile EDR
  – Dedicated Ozonesondes
    ◊ NOAA AEROSE (Nalli et al. 2011)
    ◊ CalWater/ACAPEX 2015
  – Sites of Opportunity
    ◊ SHADOZ (Thompson et al. 2007)
      o Costa Rica
      o Hanoi
      o Irene
      o Java
      o Natal
      o Paramaribo
      o Reunion
      o American Samoa
    ◊ WOUDC
      o STN043
      o STN053
      o STN107
      o STN101

From Nalli et al. (2017)

Geographic Histogram (Equal Area)
FOR Collocation Criteria: $\delta x \leq 125$ km, $-240 < \delta t < +120$ min
NUCAPS IR Ozone Profile EDR Validation
Global Ozonesondes (Including AEROSE SNPP-Dedicated)

Retrieval and *A Priori* First Guess

IR+MW Yield
= 62.2%

*From Nalli et al. (2017)*
Using Satellite EDRs as Observations

Radiosonde Launches

Humidity Cross-Sections

Environmental Satellite

Balloon-Borne Radiosondes

Blue-Water Research Vessel

Satellite

Radiosondes

Aged Air / Hadley Subsidence

AEJ

SAL

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Dry Transport: Saharan Air Layers, Hadley Cells

2013 AEROSE Radiosonde Launches (Jan-Feb 2013)

+ RAOB launch
○ nearest FOR
Zonal RH Cross-Section (SAL, Hadley Cell)
2013 AEROSE NW-SE Transect 1 (All Cases)
Moist Transport: Atmospheric Rivers
2015 CalWater/ACAPEX Radiosonde Launches (Jan-Feb 2015)

+ RAOB launch
○ nearest FOR
Temporal RH Cross-Section (All Cases)
2015 CalWater/ACAPEX Leg 2
Data taken from 2004 AEROSE campaign (after Nalli et al. 2008)
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THANK YOU!

QUESTIONS?
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EXTRA SLIDES
AVTP Statistical Summary (SAL, Hadley Cell)
2013 AEROSE RAOBs (Accepted Cases), 100 RTA Layers

Accepted FOR within 75 km radius

Launches 0–70 min prior to overpasses
Accepted FOR within 75 km radius
Launches 0–70 min prior to overpasses
AVTP Statistical Summary (AR Environment)
2015 CalWater/ACAPEX RAOBs (Accepted Cases), 100 RTA Layers

Accepted FOR within 50 km radius

Launches 0–70 min prior to overpasses
Accepted FOR within 50 km radius

Launches 0–70 min prior to overpasses