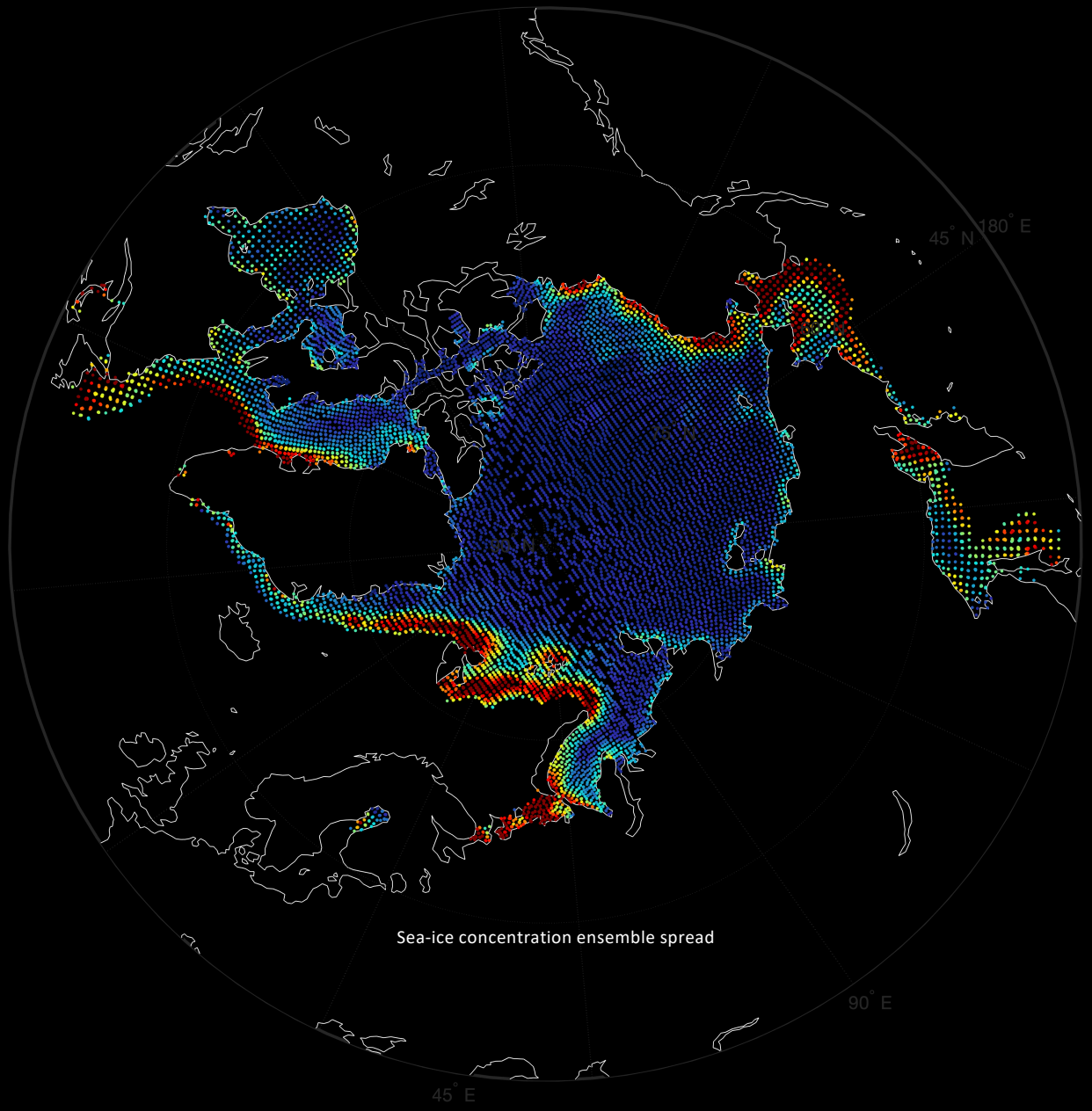
Coupled Data Assimilation in the CSIRO CAFE system

- The CSIRO Climate Analysis Forecast Ensemble (CAFE) system is an Ensemble Kalman Filter data assimilation system developed to provide state estimates using a climate model (O'Kane et al, 2019).
- The CAFE system has grown to assimilate a wide range of global historical and real-time observations similar to other international systems. These encompass both infrared and microwave SST, altimetry, ocean in-situ data, sea-ice concentration and thickness, atmospheric (re)analysis data, ocean color and soil moisture.
- The CAFE system is unique, being the first global coupled large-scale geophysical DA system to assimilate into the four realms: atmosphere, ocean, land and sea-ice, to produce analyses consistent between these realms.



Sea-ice concentration ensemble spread

Paul A. Sandery[1], Terence J. O'Kane[1], Vassili Kitsios[1], Pavel Sakov[2]
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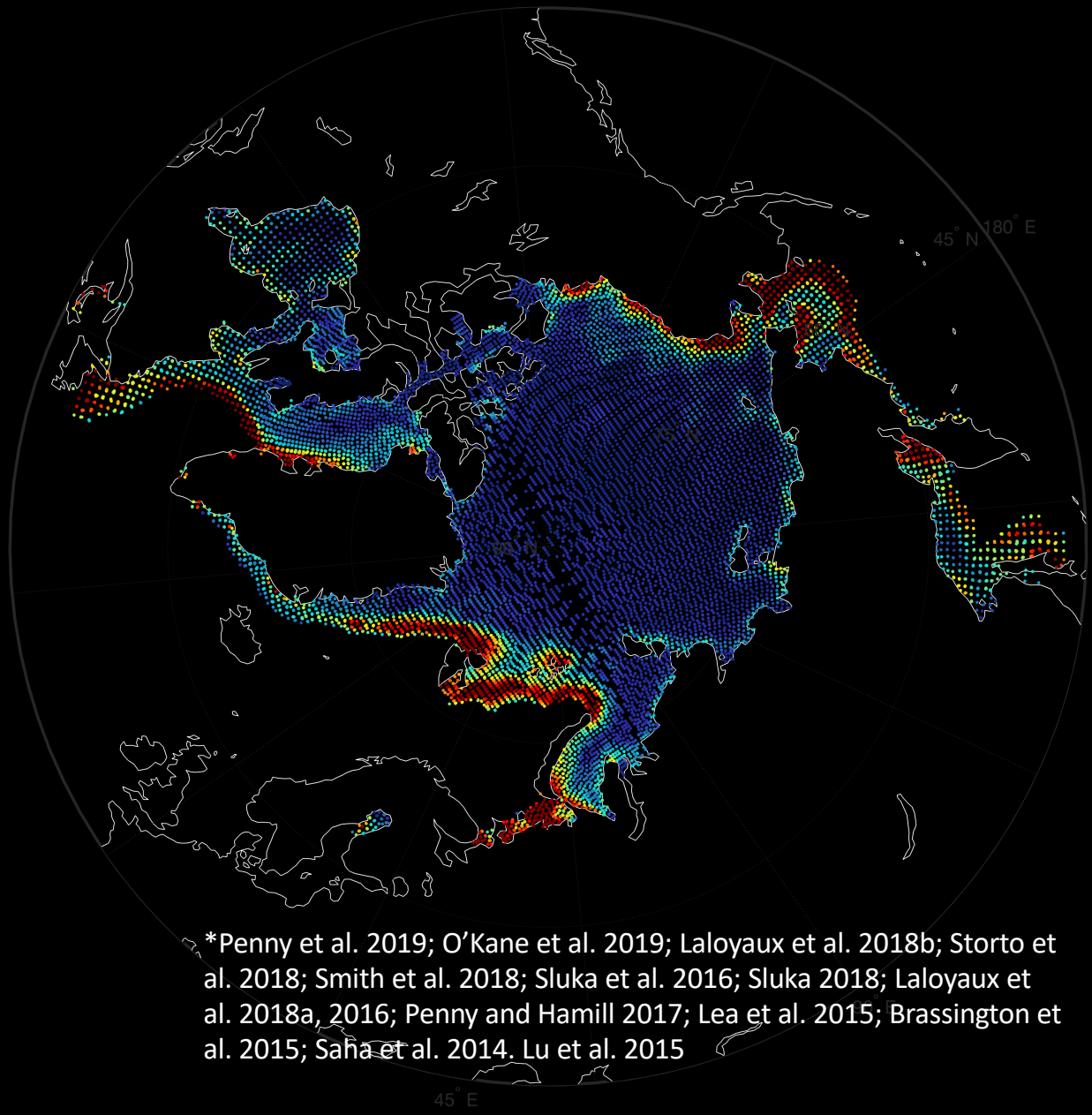
Coupled Data Assimilation in the CSIRO CAFE system

CDA Challenges

- Coupled models inherit and propagate error from component models
- Scale separation, sampling of cross-domain error covariances, model deficiencies and managing observation impact in coupled DA remains challenging*
- Some of these issues addressed by modifying the impact of observations via the cross-covariances (Sandery et al, 2020) and with asynchronous assimilation (Sakov, 2014).



*Penny et al. 2019; O'Kane et al. 2019; Laloyaux et al. 2018b; Storto et al. 2018; Smith et al. 2018; Sluka et al. 2016; Sluka 2018; Laloyaux et al. 2018a, 2016; Penny and Hamill 2017; Lea et al. 2015; Brassington et al. 2015; Sana et al. 2014. Lu et al. 2015

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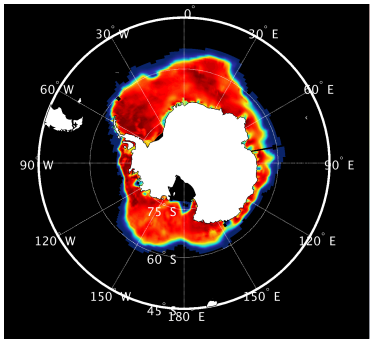
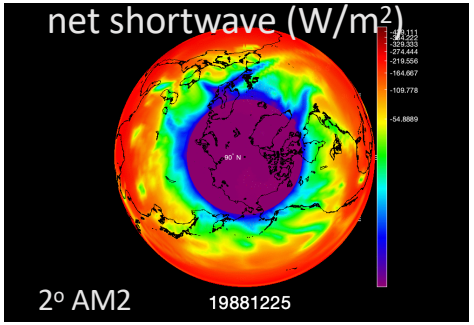
Coupled data assimilation in the CSIRO CAFE system

CAFE-EnKF

- Strongly coupled **96** member **ensemble prediction system** based on CSIRO GFDL CM2
- Assimilates comprehensive sets of remotely sensed and in-situ observations
- Aims to constrain **scales** in **atmosphere**, **ocean, sea-ice, land** realms relevant to climate analysis and forecasting and produce balanced analysis of ensemble states consistent with multiple observations across realms
- Produces comprehensive **forecast error estimates**
- Accounts for and cross-validates observation errors
- Used to study Impact of observations via **cross-domain** covariances (Sandery et al, 2020)
- Used for **CAFE-60 reanalysis** (OKane et al, 2020)
- Initialize climate forecasts – contribution to WMO Galobal Annual to Decadal Climate Update WMO with the UK Met Office (**DCFP**)
- Quantitative framework for model development via EnKF parameter estimation (Kitsios et al, 2020)





Atmosphere **AM2**

U-wind
V-wind
Air temperature
Specific humidity
Pressure

Land **LM2**

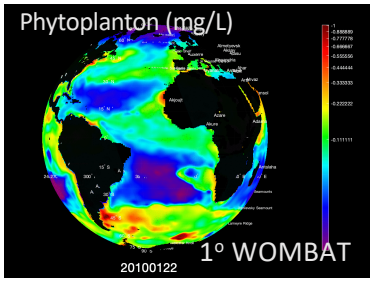
Water
Groundwater
Snow

Sea-ice **SIS**

Area
Thickness
U-velocity
V-velocity

EnKF-C (Sakov, 2020)

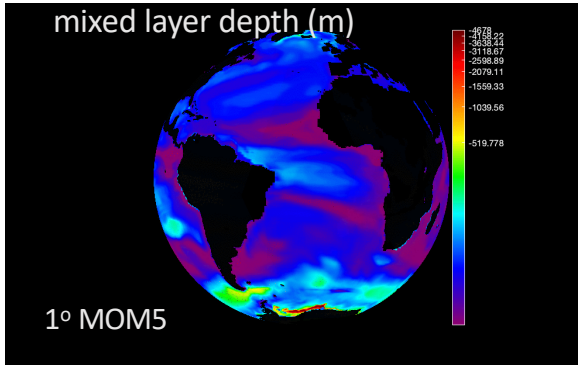
Biology **WOMBAT**



Nitrate
Phosphate
Phytoplankton
Zooplankton
$CaCO_3$
Oxygen
Alkalinity
DIC
ADIC

Ocean **MOM5**

Sea-level-anomaly
Temperature
Salinity
U-velocity
V-velocity



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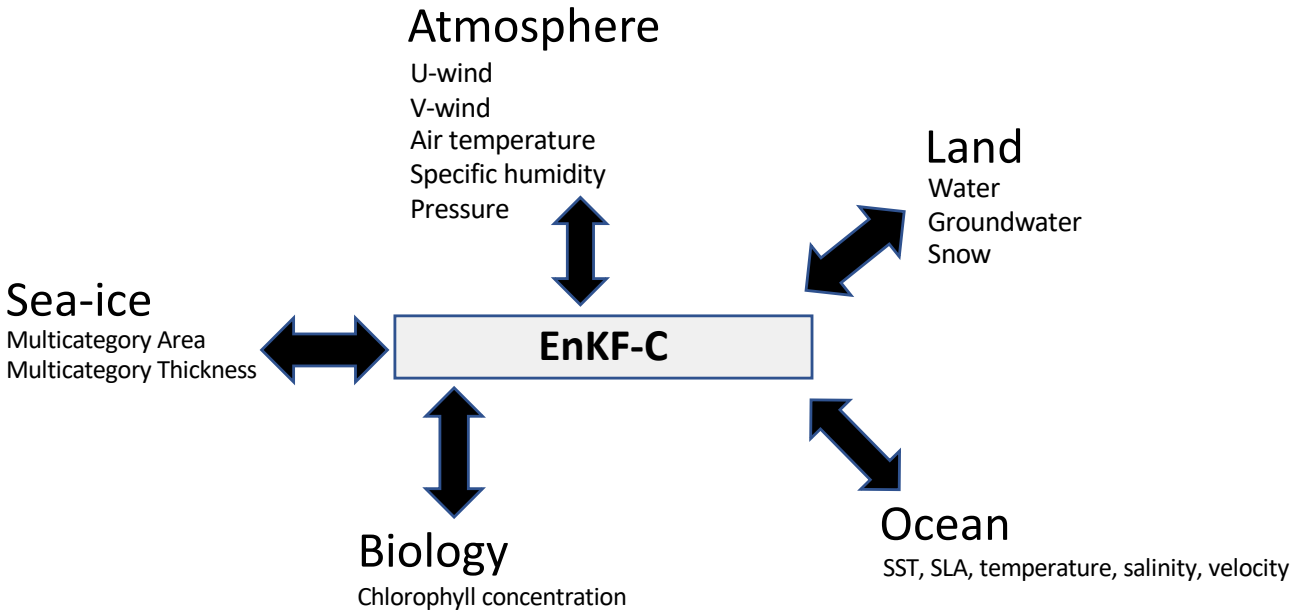
Coupled data assimilation in the CSIRO CAFE system

State Vector



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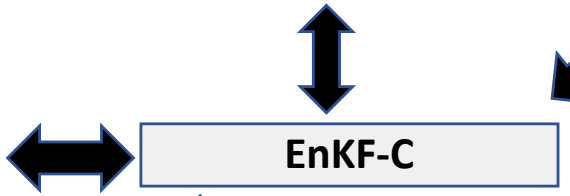
Coupled data assimilation in the CSIRO CAFE system

Observed Variables



- JRA55

Atmosphere
U-wind
V-wind
Air temperature
Specific humidity

- GRACE LWE satellite land surface water content for groundwater, water, snow

Land
Water
Groundwater
Snow

Sea-ice
Total Area
Total Thickness

- EuMetsat OSISAF 25km climate data record sea ice concentration
- ESA Cryosat2, SMOS and NASA GIOMAS sea-ice thickness

Biology
Chlorophyll concentration

- GlobColour daily merged MERIS/MODIS/SeaWiFS

Ocean
SST, SLA, temperature, salinity

- RADS4 altimetry from 1993-2020
- ESA CCI-SST, VIIRS, MetOpA, NAVO-AVHRR, NOAA-19 + others
- In-situ temperature and salinity from **CORA5** including gliders, drifters, profilers, RV-CTD, XBT, MBT, XCTD, bottles, CTD, XBT, moorings, marine mammals etc.
- BoM MMT in-situ T/S 2018-2020+

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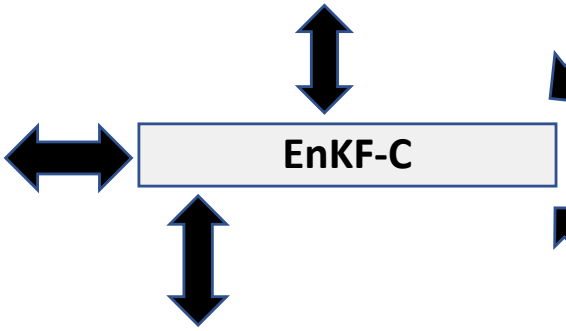
Coupled data assimilation in the CSIRO CAFE system

Observed Variables



RFACTOR=16
LOCRAD=2000 km

- JRA55

Atmosphere
U-wind
V-wind
Air temperature
Specific humidity

RFACTOR=1
LOCRAD=500 km

- GRACE LWE satellite land surface water content for groundwater, water, snow

Land
Water
Groundwater
Snow

Sea-ice
Total Area
Total Thickness

- EuMetsat OSISAF 25km climate data record sea ice concentration
- ESA Cryosat2, SMOS and NASA GIOMAS sea-ice thickness

RFACTOR SIC=1
LOCRAD SIC=500 km
RFACTOR SIH=1
LOCRAD SIH=500 km

Biology
Chlorophyll concentration

- GlobColour daily merged MERIS/MODIS/SeaWiFS

RFACTOR PHY=1
LOCRAD PHY=500 km

Ocean
SST, SLA, temperature, salinity

RFACTOR SST=16
LOCRAD SST=500 km
RFACTOR TEM=1
LOCRAD TEM=1000 km
RFACTOR SAL=1
LOCRAD SAL=1000 km
RFACTOR TEM2=64
LOCRAD TEM2=1000 km
RFACTOR SAL2=64
LOCRAD SAL2=1000 km
RFACTOR SLA=2
LOCRAD SLA=1000km

- RADS4 altimetry from 1993-2020
- ESA CCI-SST, VIIRS, MetOpA, NAVO-AVHRR, NOAA-19 + others
- In-situ temperature and salinity from **CORA5** including gliders, drifters, profilers, RV-CTD, XBT, MBT, XCTD, bottles, CTD, XBT, moorings, marine mammals etc.
- BoM MMT in-situ T/S 2018-2020+

RFACTOR - multiplicative observation error factor, LOCRAD – localization radius

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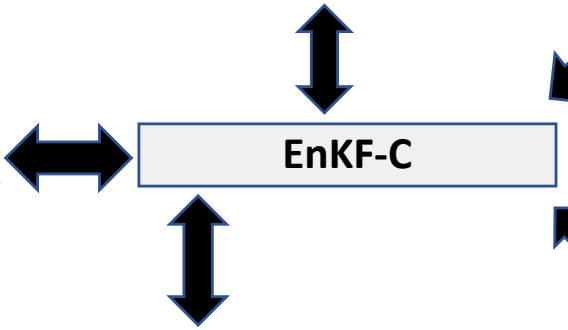
Coupled data assimilation in the CSIRO CAFE system

Observed Variables

DOMAINS

- Control whether an observation type from one realm influences that of another realm in the coupled analysis (Sandery et al 2020)



RFACTOR=16
LOCRAD=2000 km

- JRA55

RFACTOR=1
LOCRAD=500 km

- GRACE LWE satellite land surface water content for groundwater, water, snow

- EuMetsat OSISAF 25km climate data record sea ice concentration
- ESA Cryosat2, SMOS and NASA GIOMAS sea-ice thickness

RFACTOR SIC=1
LOCRAD SIC=500 km
RFACTOR SIH=1
LOCRAD SIH=500 km

- GlobColour daily merged MERIS/MODIS/SeaWiFS

RFACTOR PHY=1
LOCRAD PHY=500 km

RFACTOR SST=16
LOCRAD SST=500 km
RFACTOR TEM=1
LOCRAD TEM=1000 km
RFACTOR SAL=1
LOCRAD SAL=1000 km
RFACTOR TEM2=64
LOCRAD TEM2=1000 km
RFACTOR SAL2=64
LOCRAD SAL2=1000 km
RFACTOR SLA=2
LOCRAD SLA=1000km

- RADS4 altimetry from 1993-2020
- ESA CCI-SST, VIIRS, MetOpA, NAVO-AVHRR, NOAA-19 + others
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- BoM MMT in-situ T/S 2018-2020+

RFACTOR - multiplicative observation error factor, LOCRAD – localization radius

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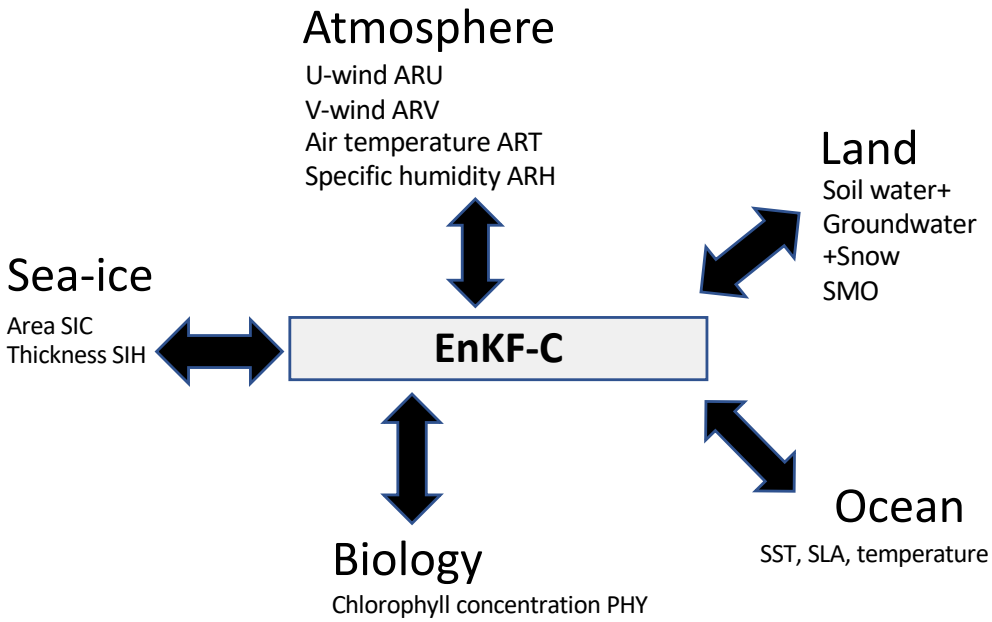
Coupled data assimilation in the CSIRO CAFE system

```
printing observation summary:
  type    #used    #dropped #out_grd #out_obs #out_wnd #land    #shallow #badbatch#badvalue#thinned #superobs
  ------------------------------------------------------------------------------------------------------------
  SLA     887151   61276    0        0        0        2084     59192    0        0        0        100697
  SST    102825533 998014   0        0        59618    938396   0        0        0        0        801571
  SST2    4587926  59304    0        0        0        59304    0        0        0        0        502474
  TEM     2115404  32974    0        0        0        32974    0        0        0        0        115811
  TEM2    126868   8411     0        0        0        8411     0        0        0        0        5596
  SAL     1805940  51037    0        0        0        42161    0        0        8876     0        102645
  SAL2    2755     7349     0        0        0        7349     0        0        0        0        344
  SSS     1022042  3808     0        0        0        1997     0        0        1811     0        108522
  ART     7928494  1688666  85806    0        0        1602860  0        0        0        0        2185253
  ARH     7928494  1688666  85806    0        0        1602860  0        0        0        0        2185253
  ARU     7928494  1688666  85806    0        0        1602860  0        0        0        0        2185253
  ARV     7928494  1688666  85806    0        0        1602860  0        0        0        0        2185253
  SIC     1718913  21343    0        0        0        21343    0        0        0        0        251552
  SIT     255856   1484400  0        0        0        21343    0        0        1463057  0        82780
  SIH     0        0        0        0        0        0        0        0        0        0        0
  SIH2    6456     51930    0        0        0        16054    0        0        35876    0        5413
  SMO     473871   561489   0        0        0        550100   0        0        11389    0        6694
  total   147542691 10095999 343224  0        59618    8112956  59192    0        1521009  0        10825111
2020-11-17 15:19:49
finished
```

- Observations for a typical 7 day coupled analysis from 20150909




```
# obs with increased error due
  to subgrid variability:
  SLA 21622 (21.47%)
  SST 243436 (30.37%)
  SST2 20921 (4.16%)
  TEM 9215 (7.96%)
  TEM2 165 (2.95%)
  SAL 3937 (3.84%)
  SAL2 1 (0.29%)
  SSS 2239 (2.06%)
  ART 1042247 (47.69%)
  ARU 787902 (36.06%)
  ARV 639263 (29.25%)
  SIC 14894 (5.92%)
  SMO 3580 (53.48%)
```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- **JRA55** atmospheric reanalysis wind, temperature, humidity, pressure
- **Satellite SST** from 1993-2020 ESA CCI SST, VIIRS, NAVO, AMSR-2 + others
- **RADS4** altimetry from 1993-2020
- In-situ temperature and salinity from **CORA5** including gliders, drifters, profilers, RV-CTD, XBT, MBT, XCTD, bottles, CTD, XBT, moorings, marine mammals etc.
- BoM MMT in-situ T/S 2018-2020+
- EuMetsat OSISAF 10 and 25km climate data record sea ice concentration
- ESA Cryosat2, SMOS and NASA GIOMAS sea-ice thickness
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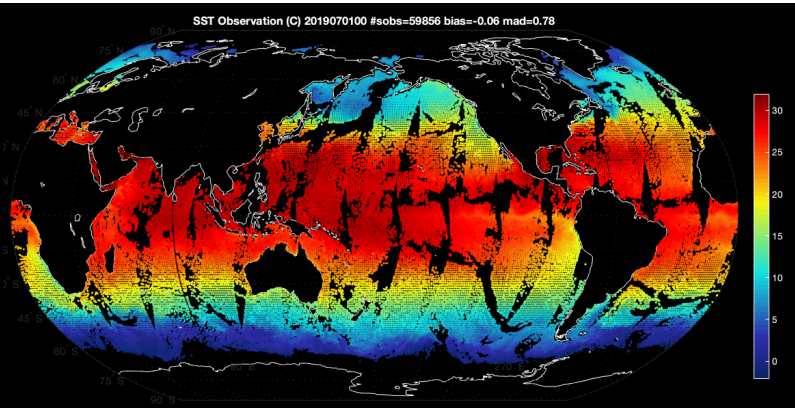
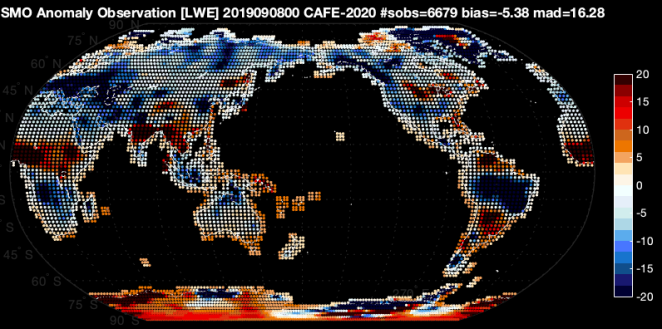
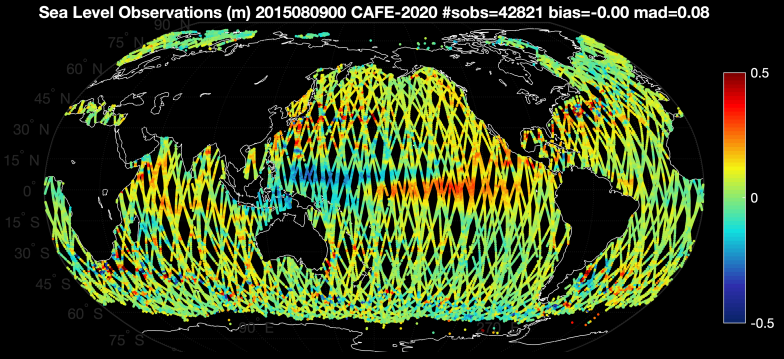
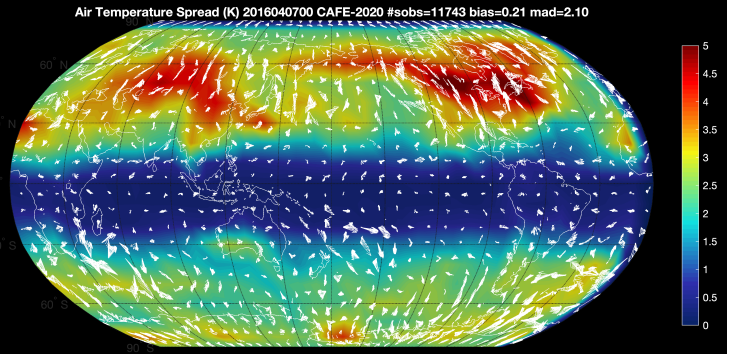
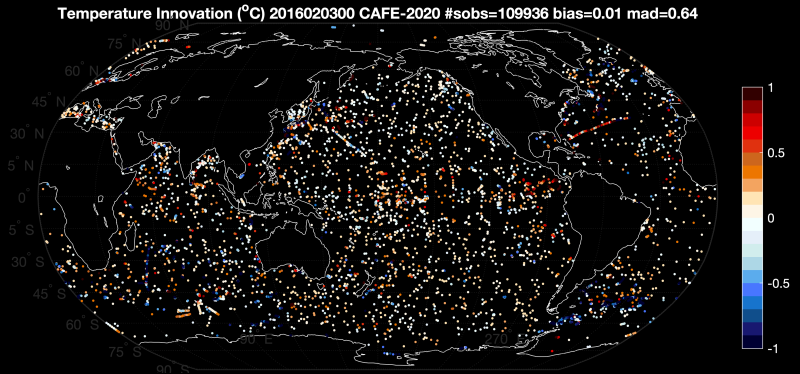
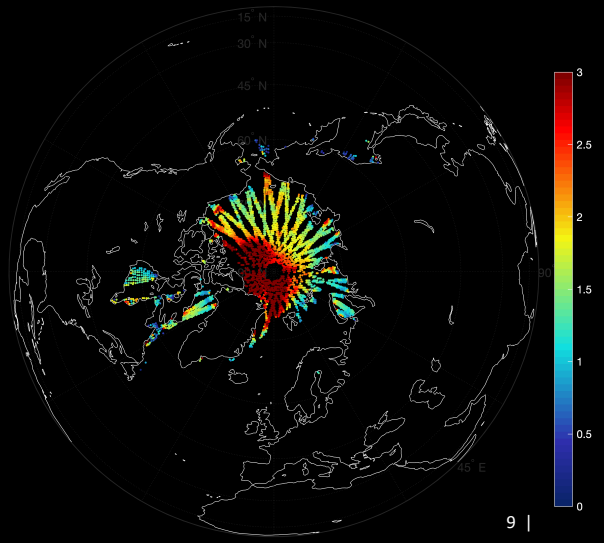


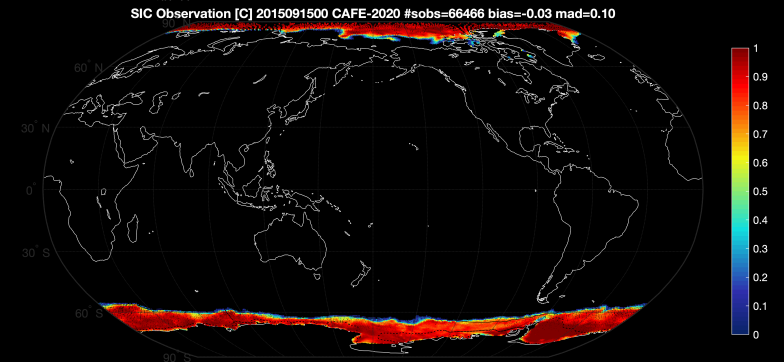








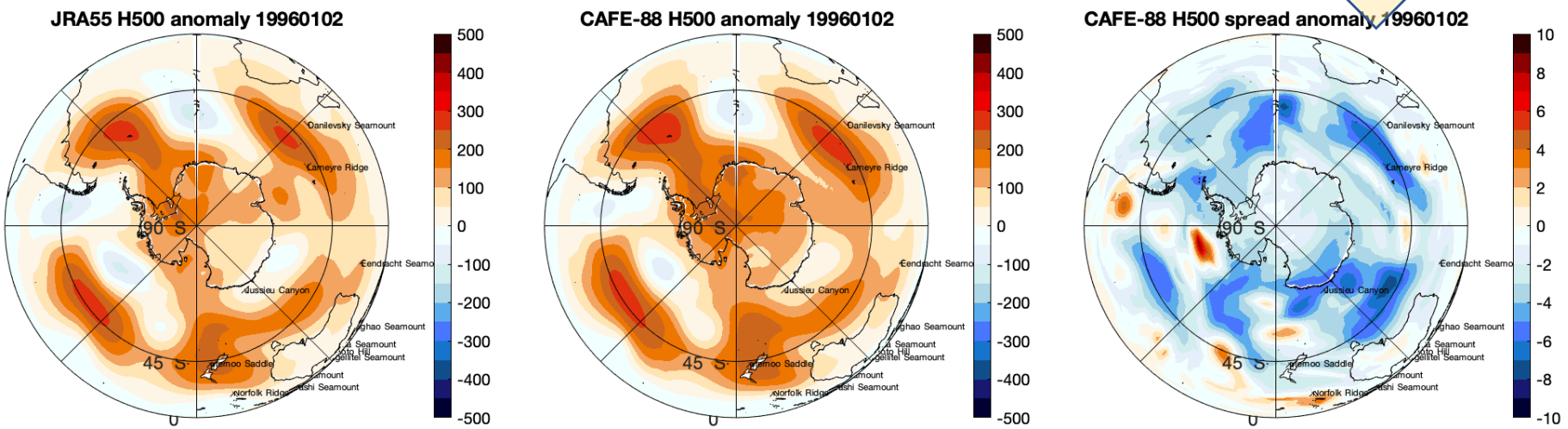




Coupled data assimilation in the CSIRO CAFE system

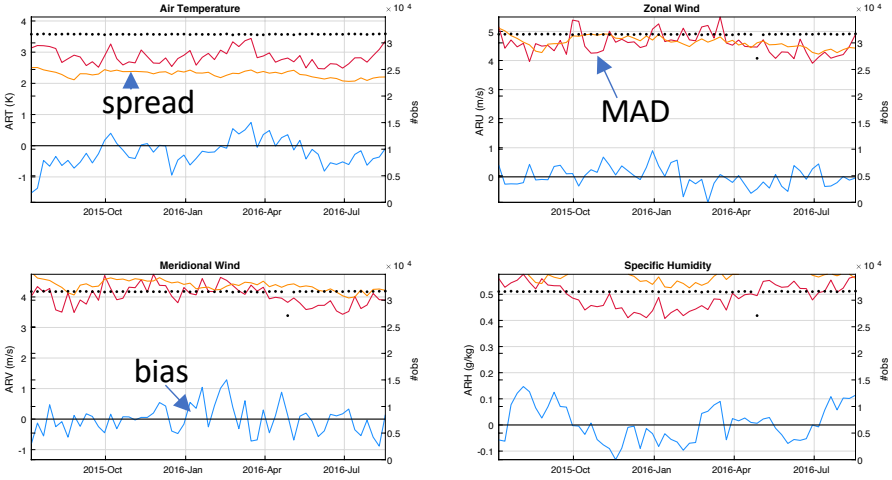
- **Ensemble mean atmospheric states after assimilation of JRA55**

1 DAY CYCLE



7 DAY CYCLE

```
printing observation statistics:
    region obs.type   # obs.  |for.inn.| |an.inn.|   for.inn.   an.inn.  for.spread  an.spread
  ------------------------------------------------------------------------------------------
       ART    141631    2.520     1.533    -0.672    -0.690     2.080     1.344
        -6     20233    2.391     1.558    -0.766    -0.749     1.812     1.177
        -5     20233    2.515     1.557    -0.630    -0.633     2.002     1.231
        -4     20233    2.541     1.517    -0.583    -0.636     2.006     1.296
        -3     20233    2.587     1.570    -0.663    -0.734     2.118     1.367
        -2     20233    2.555     1.511    -0.654    -0.686     2.180     1.410
        -1     20233    2.546     1.491    -0.666    -0.682     2.243     1.447
         0     20233    2.507     1.528    -0.743    -0.707     2.295     1.484
       JRA    141631    2.520     1.533    -0.672    -0.690     2.080     1.344
       ARU    141631    4.131     1.805     0.190     0.081     4.471     2.870
        -6     20233    3.800     1.891    -0.059    -0.020     3.777     2.436
        -5     20233    4.064     1.876    -0.053     0.024     4.066     2.612
        -4     20233    3.999     1.752     0.142     0.054     4.301     2.759
        -3     20233    4.318     1.817     0.505     0.227     4.551     2.919
        -2     20233    4.255     1.743     0.344     0.112     4.751     3.045
        -1     20233    4.137     1.705     0.173     0.035     4.874     3.123
         0     20233    4.345     1.850     0.275     0.137     4.976     3.198
       JRA    141631    4.131     1.805     0.190     0.081     4.471     2.870
       ARV    141631    3.754     1.504    -0.029     0.007     4.324     2.771
        -6     20233    3.848     1.682    -0.054    -0.030     3.673     2.368
        -5     20233    4.139     1.667    -0.060    -0.010     3.945     2.533
        -4     20233    4.017     1.650    -0.053     0.045     4.200     2.691
        -3     20233    3.708     1.479    -0.016     0.020     4.401     2.816
        -2     20233    3.470     1.299    -0.001     0.021     4.549     2.908
        -1     20233    3.437     1.311     0.008     0.001     4.679     2.992
         0     20233    3.655     1.439    -0.026     0.002     4.821     3.091
       JRA    141631    3.754     1.504    -0.029     0.007     4.324     2.771
```



- **Asynchronous assimilation into atmosphere of gridded data filters for scale separation in this system**

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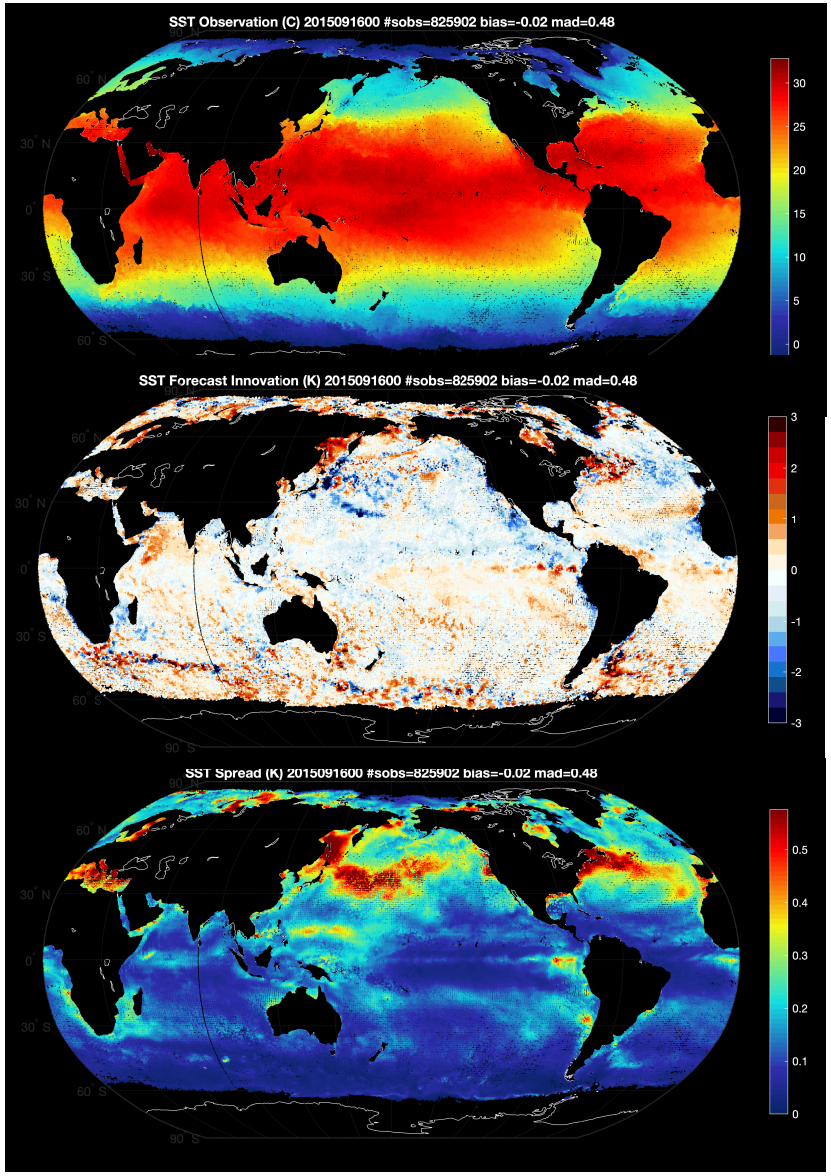
Coupled data assimilation in the CSIRO CAFE system

- **Asynchronous assimilation**

```
printing observation statistics:
  region obs.type    # obs.   |for.inn.| |an.inn.|   for.inn.   an.inn.  for.spread  an.spread
  ------------------------------------------------------------------------------------------
  Global
         SST         258308    0.449     0.331     -0.006      0.002      0.174      0.113
          -6          35812    0.393     0.309      0.005      0.013      0.144      0.095
          -5          36092    0.421     0.323     -0.011      0.000      0.156      0.102
          -4          37364    0.439     0.329     -0.032     -0.015      0.162      0.106
          -3          36777    0.464     0.345     -0.012     -0.001      0.172      0.112
          -2          37377    0.472     0.343     -0.012     -0.005      0.184      0.119
          -1          37202    0.474     0.334      0.007      0.011      0.194      0.126
           0          37684    0.476     0.332      0.016      0.013      0.202      0.132
           AMSR-2     56406    0.499     0.390      0.060      0.065      0.173      0.113
           NOAA-19    65650    0.460     0.338     -0.032     -0.022      0.179      0.117
           MetOpA     60863    0.435     0.313     -0.042     -0.034      0.174      0.113
           AVHRR      75389    0.413     0.295     -0.003      0.006      0.169      0.111
         SST2         129458    0.447     0.369      0.042      0.062      0.153      0.101
          -6          18494    0.426     0.376      0.040      0.062      0.130      0.087
          -5          18494    0.433     0.373      0.032      0.055      0.137      0.091
          -4          18494    0.443     0.373      0.033      0.058      0.145      0.096
          -3          18494    0.449     0.369      0.039      0.062      0.153      0.101
          -2          18494    0.454     0.365      0.048      0.069      0.161      0.106
          -1          18494    0.460     0.364      0.050      0.065      0.169      0.111
           0          18494    0.462     0.364      0.048      0.059      0.177      0.117
           OISST      129458    0.447     0.369      0.042      0.062      0.153      0.101
```



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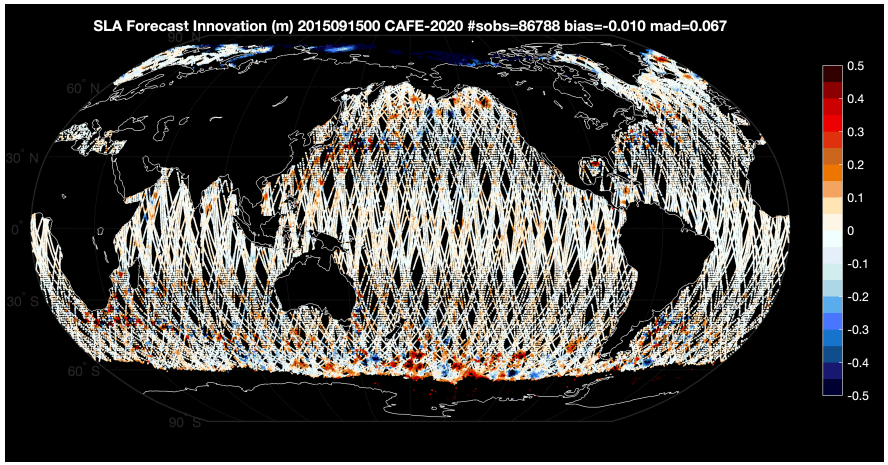
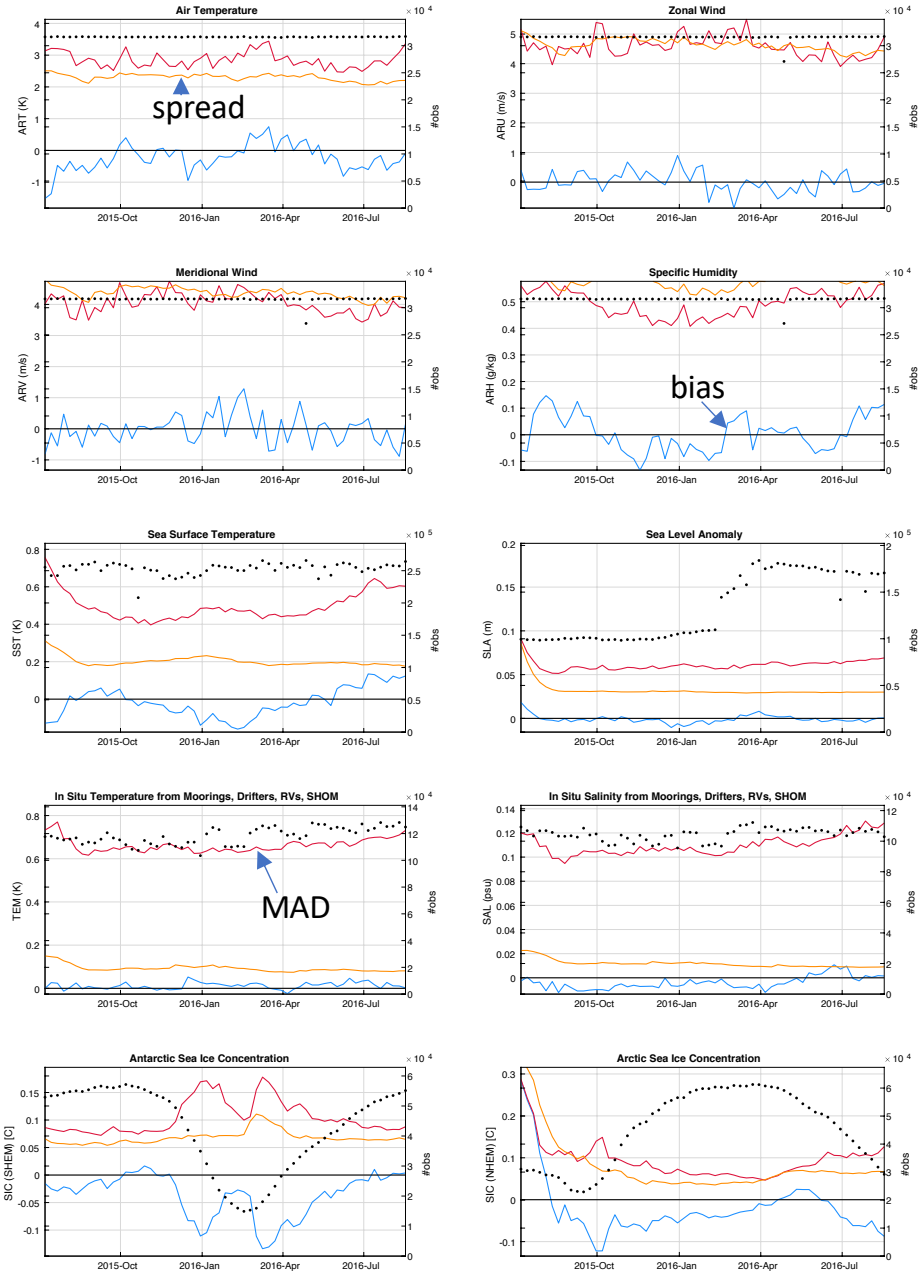
Coupled data assimilation in the CSIRO CAFE system

- **Global forecast innovation MAD, bias, spread**

```
printing observation statistics:
  region obs.type   # obs.  |for.inn.| |an.inn.|   for.inn.   an.inn.  for.spread  an.spread
  ------------------------------------------------------------------------------------------
  Global
         SLA        100697    0.056     0.044     -0.004     -0.002      0.030      0.020
          -6         14405    0.054     0.043     -0.006     -0.004      0.029      0.019
          -5         14244    0.054     0.043     -0.004     -0.002      0.029      0.019
          -4         14464    0.056     0.044     -0.002      0.000      0.030      0.019
          -3         14394    0.057     0.044     -0.004     -0.002      0.030      0.020
          -2         14337    0.059     0.046     -0.001     -0.001      0.031      0.020
          -1         14494    0.058     0.045     -0.005     -0.004      0.031      0.020
           0         14359    0.058     0.044     -0.004     -0.003      0.032      0.021
          c2         31685    0.058     0.046     -0.004     -0.002      0.030      0.020
          j2         33606    0.052     0.041      0.001      0.000      0.030      0.020
          sa         35406    0.060     0.046     -0.008     -0.005      0.030      0.020
         SST        250010    0.458     0.335      0.040      0.025      0.178      0.116
          -6         37020    0.402     0.317      0.041      0.029      0.154      0.102
          -5         37964    0.418     0.321      0.048      0.032      0.164      0.107
          -4         30197    0.433     0.319      0.032      0.014      0.172      0.112
          -3         29929    0.456     0.330      0.021      0.008      0.178      0.116
          -2         39967    0.484     0.350      0.062      0.045      0.187      0.122
          -1         37537    0.495     0.350      0.045      0.027      0.192      0.125
           0         37387    0.509     0.354      0.025      0.012      0.199      0.130
           1             9    0.392     0.343      0.286      0.259      0.407      0.261
        AMSR-2       42787    0.516     0.398      0.122      0.107      0.181      0.119
      NOAA-19        67170    0.472     0.347      0.023      0.005      0.183      0.119
        MetOpA       63359    0.449     0.324      0.017      0.000      0.178      0.116
         AVHRR       76694    0.419     0.300      0.029      0.016      0.173      0.113
         SST2       129458    0.464     0.391      0.053      0.050      0.159      0.105
          -6         18494    0.425     0.377      0.066      0.066      0.137      0.092
          -5         18494    0.435     0.376      0.059      0.058      0.144      0.095
          -4         18494    0.449     0.380      0.050      0.050      0.152      0.100
          -3         18494    0.464     0.387      0.047      0.045      0.159      0.105
          -2         18494    0.478     0.395      0.049      0.045      0.167      0.109
          -1         18494    0.496     0.407      0.054      0.048      0.174      0.115
           0         18494    0.503     0.413      0.048      0.042      0.181      0.120
       OISST        129458    0.464     0.391      0.053      0.050      0.159      0.105
```





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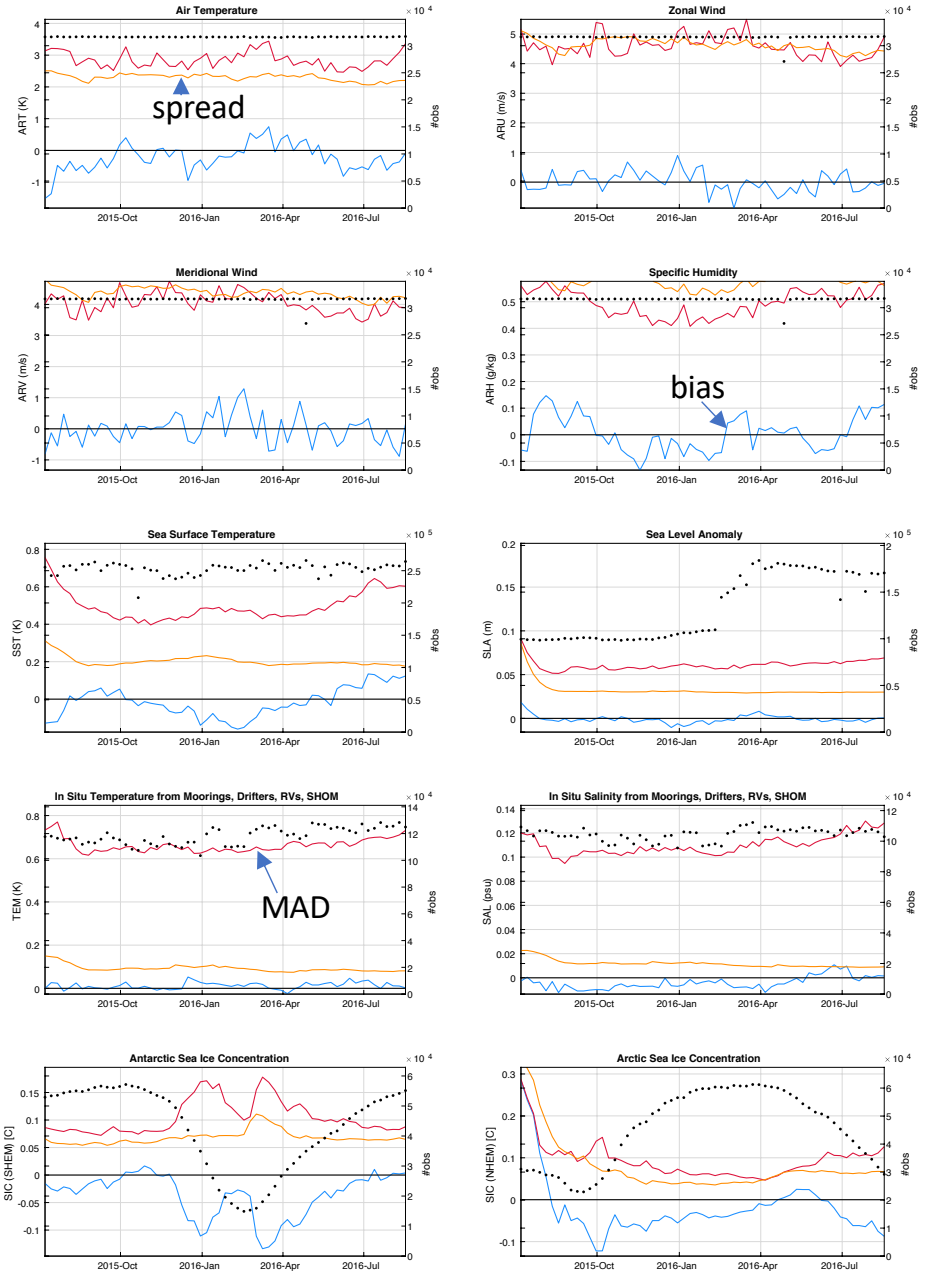
Coupled data assimilation in the CSIRO CAFE system

- **Global forecast innovation MAD, bias, spread**

```
printing observation statistics:
  region obs.type   # obs.  |for.inn.| |an.inn.|   for.inn.   an.inn.  for.spread  an.spread
  ------------------------------------------------------------------------------------------
  Global
         TEM        122310    0.695     0.581      0.038      0.031      0.080      0.058
          -6         17758    0.638     0.545      0.015      0.014      0.069      0.052
          -5         16548    0.638     0.541      0.059      0.041      0.072      0.053
          -4         17268    0.670     0.556      0.056      0.040      0.075      0.055
          -3         16808    0.688     0.571      0.028      0.020      0.081      0.059
          -2         18436    0.742     0.613      0.031      0.021      0.082      0.059
          -1         18586    0.766     0.645      0.045      0.045      0.087      0.063
           0         16906    0.716     0.591      0.032      0.036      0.093      0.066
         WMO865       2331    0.563     0.499     -0.037     -0.019      0.043      0.033
         WMO853       9672    0.627     0.501     -0.034     -0.028      0.067      0.049
         WMO846      51131    0.674     0.575      0.019      0.021      0.064      0.048
         WMO869         71    0.327     0.327     -0.010     -0.012      0.053      0.041
         WMO742         29    1.637     1.563      1.459      1.385      0.091      0.074
         WMO844      11027    0.646     0.557      0.013      0.014      0.069      0.052
         WMO995       2754    0.455     0.406     -0.136     -0.102      0.053      0.039
         WMO841       2963    0.734     0.614      0.042      0.032      0.101      0.074
         WMO830       3013    1.324     1.142      0.134      0.203      0.076      0.056
         WMO231        142    2.320     2.159      1.526      1.451      0.106      0.078
         WMO862        431    0.573     0.405      0.357      0.181      0.051      0.036
         WMO052       2328    0.886     0.719      0.156      0.106      0.070      0.053
         WMO851       5547    0.604     0.521      0.117      0.092      0.057      0.044
         WMO839        911    0.579     0.492      0.008      0.001      0.056      0.041
         WMO051       1809    0.763     0.642      0.158      0.093      0.077      0.056
         WMO854       6001    0.632     0.509      0.067      0.038      0.074      0.054
         WMO863       8565    0.790     0.623      0.101      0.045      0.081      0.059
         WMO848         35    0.138     0.131      0.026      0.025      0.013      0.013
         WMO999        583    1.014     0.856     -0.099     -0.109      0.122      0.085
         WMO820       3882    1.087     0.899      0.224      0.118      0.144      0.109
         WMO000        109    0.522     0.312      0.390      0.242      0.113      0.077
         WMO866        330    0.507     0.411     -0.340     -0.202      0.041      0.031
         WMO741         34    1.025     1.056      0.840      0.923      0.100      0.070
         WMO011         23    0.199     0.168      0.174      0.141      0.030      0.022
         WMO860         25    3.445     3.159      3.445      3.159      0.064      0.048
         WMO212         26    0.857     0.863      0.014      0.154      0.111      0.078
         WMO042         23    0.586     0.576      0.225      0.187      0.031      0.022
         WMO838         80    0.429     0.421      0.285      0.164      0.037      0.031
         WMO222         32    1.642     1.621      1.305      1.208      0.097      0.073
         WMO1017       449    0.917     0.788     -0.621     -0.479      0.082      0.058
         WMO1025       178    0.941     0.824      0.672      0.567      0.112      0.076
         WMO1111      7475    0.541     0.406     -0.018      0.015      0.225      0.147
         WMO1051         7    0.921     0.686     -0.921     -0.686      0.420      0.278
         WMO1049        17    0.155     0.172      0.143      0.167      0.054      0.035
         WMO872        217    0.887     0.512      0.586      0.234      0.092      0.065
         WMO1016        10    0.786     0.830     -0.128     -0.290      0.259      0.172
         WMO1033        16    0.423     0.437      0.349      0.393      0.179      0.115
         WMO1003        32    0.644     0.355      0.106      0.211      0.433      0.277
         WMO1036         2    1.370     0.941      1.370      0.941      0.196      0.138
         0-50m       26575    0.663     0.520      0.095      0.080      0.168      0.115
         50-500m     71495    0.837     0.703      0.020      0.015      0.070      0.053
         500-9999m   24240    0.313     0.291      0.028      0.023      0.013      0.011
        TEM2         10541    0.888     0.765     -0.020      0.003      0.078      0.058
          -6          1376    0.821     0.694      0.200      0.155      0.062      0.048
          -5          1475    0.829     0.713      0.068      0.083      0.063      0.047
          -4          1385    0.694     0.586     -0.106     -0.105      0.074      0.056
          -3          1400    0.836     0.721     -0.397     -0.332      0.070      0.053
          -2          1746    0.835     0.724      0.124      0.103      0.079      0.058
          -1          1923    1.204     1.051     -0.069      0.023      0.094      0.069
           0          1236    0.890     0.771      0.023      0.067      0.100      0.074
         WMO865         36    0.414     0.407      0.023      0.011      0.031      0.021
         WMO742         31    1.560     1.489      1.337      1.268      0.087      0.071
         WMO995       2784    0.459     0.410     -0.132     -0.098      0.053      0.039
         WMO830       1929    1.592     1.380     -0.282     -0.102      0.111      0.086
         WMO231        142    2.320     2.159      1.526      1.451      0.106      0.078
         0-50m        2341    0.899     0.741     -0.019      0.036      0.160      0.113
         50-500m      7184    0.925     0.801     -0.048     -0.028      0.059      0.046
         500-9999m    1016    0.597     0.567      0.169      0.144      0.020      0.017
```



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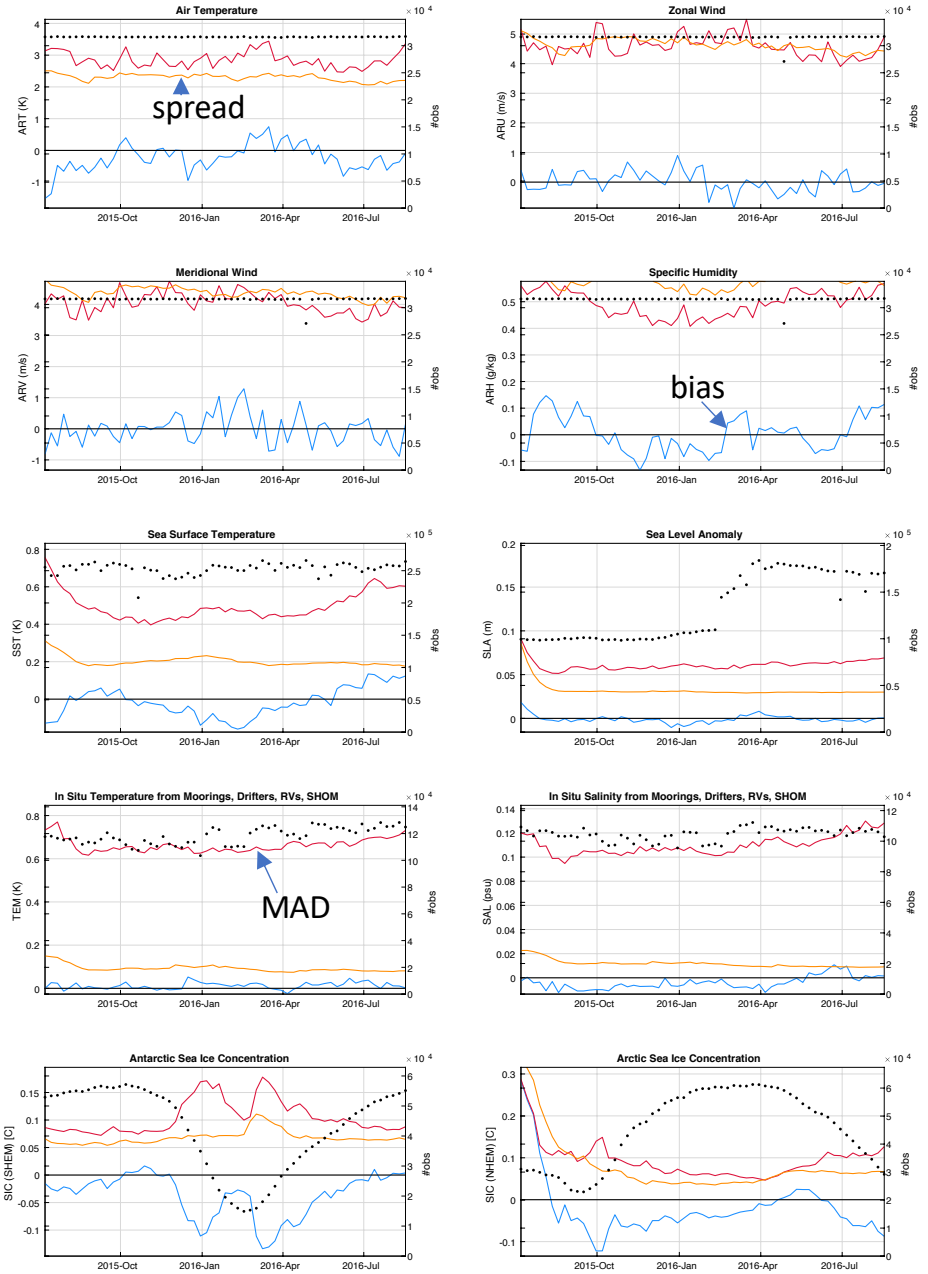
Coupled data assimilation in the CSIRO CAFE system

- **Global forecast innovation MAD, bias, spread**

printing observation statistics:

region	obs.type	# obs.	|for.inn.|	|an.inn.|	for.inn.	an.inn.	for.spread	an.spread
	SAL	102645	0.102	0.090	-0.009	-0.007	0.011	0.009
	-6	14767	0.101	0.090	-0.003	-0.003	0.010	0.008
	-5	15281	0.101	0.089	-0.012	-0.011	0.011	0.009
	-4	14493	0.096	0.085	-0.005	-0.005	0.011	0.009
	-3	14863	0.098	0.086	-0.006	-0.003	0.012	0.009
	-2	13870	0.106	0.093	-0.009	-0.006	0.012	0.009
	-1	14418	0.107	0.093	-0.017	-0.016	0.012	0.009
	0	14953	0.103	0.092	-0.010	-0.007	0.013	0.010
	WMO844	10872	0.100	0.087	0.007	0.006	0.012	0.010
	WMO846	49235	0.093	0.083	-0.006	-0.006	0.011	0.008
	WMO863	7718	0.099	0.088	-0.012	-0.003	0.012	0.009
	WMO839	2352	0.093	0.079	-0.033	-0.031	0.009	0.007
	WMO999	532	0.053	0.076	0.011	0.056	0.008	0.006
	WMO851	5833	0.083	0.070	-0.012	-0.008	0.010	0.008
	WMO995	2936	0.144	0.125	0.052	0.049	0.011	0.009
	WMO841	3888	0.081	0.069	-0.001	-0.000	0.012	0.010
	WMO830	3534	0.185	0.155	-0.061	-0.046	0.016	0.012
	WMO820	1324	0.145	0.098	-0.030	-0.027	0.037	0.026
	WMO865	1639	0.100	0.096	0.007	0.006	0.010	0.008
	WMO862	389	0.051	0.057	0.002	0.046	0.007	0.005
	WMO741	40	0.653	0.610	-0.333	-0.297	0.047	0.036
	WMO853	9182	0.080	0.070	-0.007	-0.007	0.012	0.009
	WMO854	1107	0.071	0.059	0.007	0.012	0.010	0.008
	WMO000	752	0.143	0.136	0.041	0.058	0.013	0.009
	WMO745	30	0.112	0.116	-0.027	-0.031	0.023	0.016
	WMO860	141	0.092	0.082	0.032	0.028	0.008	0.007
	WMO837	66	0.101	0.140	-0.089	-0.134	0.007	0.005
	WMO838	151	0.084	0.063	0.053	0.030	0.008	0.006
	WMO848	14	0.029	0.027	0.017	0.015	0.003	0.003
	WMO1017	655	0.204	0.199	-0.048	-0.026	0.012	0.009
	WMO1025	54	6.049	6.033	-5.920	-5.950	0.017	0.012
	WMO1011	14	0.142	0.082	0.004	-0.006	0.043	0.030
	WMO1041	51	0.154	0.132	0.007	-0.023	0.017	0.013
	WMO1028	14	0.142	0.128	-0.012	-0.018	0.055	0.043
	WMO1003	53	0.405	0.358	-0.401	-0.354	0.023	0.018
	WMO1033	31	0.348	0.305	-0.272	-0.231	0.047	0.034
	WMO1008	28	0.538	0.368	0.532	0.362	0.118	0.092
	WMO1051	7	0.225	0.252	-0.225	-0.252	0.019	0.013
	WMO1045	3	0.087	0.055	0.087	0.034	0.025	0.017
	0-50m	16999	0.198	0.165	-0.052	-0.050	0.029	0.022
	50-500m	61554	0.099	0.088	-0.002	0.001	0.010	0.008
	500-9999m	24092	0.040	0.042	0.003	0.003	0.002	0.002
	SAL2	344	0.119	0.114	0.069	0.072	0.007	0.005
	-6	15	0.123	0.121	0.117	0.117	0.004	0.003
	-5	71	0.106	0.109	0.094	0.103	0.006	0.004
	-4	58	0.086	0.091	0.044	0.058	0.005	0.004
	-3	43	0.149	0.131	0.134	0.117	0.006	0.004
	-2	44	0.111	0.106	0.055	0.052	0.006	0.004
	-1	45	0.111	0.108	0.078	0.075	0.006	0.004
	0	68	0.151	0.137	0.016	0.024	0.010	0.008
	WMO999	210	0.095	0.092	0.065	0.066	0.006	0.004
	WMO995	134	0.156	0.149	0.076	0.081	0.008	0.006
	0-50m	68	0.100	0.078	0.075	0.061	0.018	0.012
	50-500m	246	0.113	0.114	0.059	0.065	0.004	0.003
	500-9999m	30	0.206	0.195	0.141	0.157	0.003	0.002
	SSS	108522	0.497	0.489	0.053	0.051	0.048	0.042
	-6	54260	0.492	0.484	0.057	0.055	0.046	0.041
	-5	0	-nan	-nan	-nan	-nan	-nan	-nan
	-4	0	-nan	-nan	-nan	-nan	-nan	-nan
	-3	0	-nan	-nan	-nan	-nan	-nan	-nan
	-2	54262	0.502	0.493	0.049	0.046	0.050	0.043
	SMOS	108522	0.497	0.489	0.053	0.051	0.048	0.042



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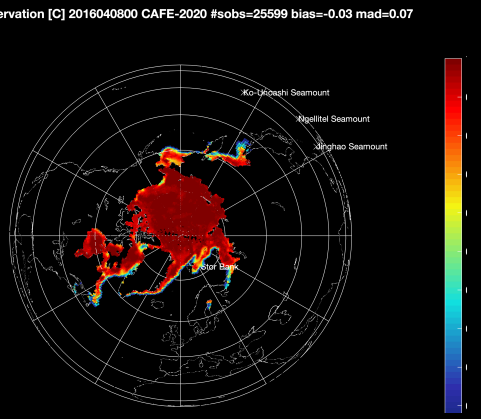
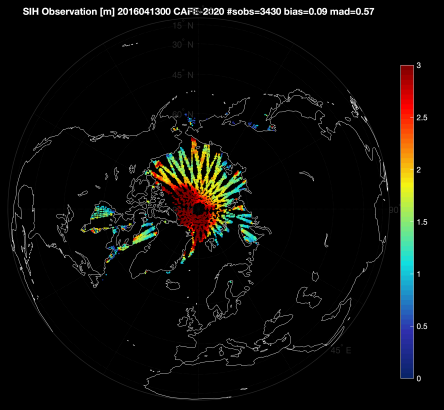
Coupled data assimilation in the CSIRO CAFE system

Assimilation of ESA SMOS-L4 sea ice thickness and OSISAF sea-ice concentration data

Sea-ice concentration [C]

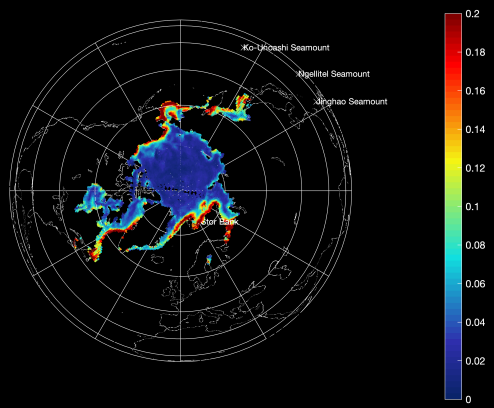


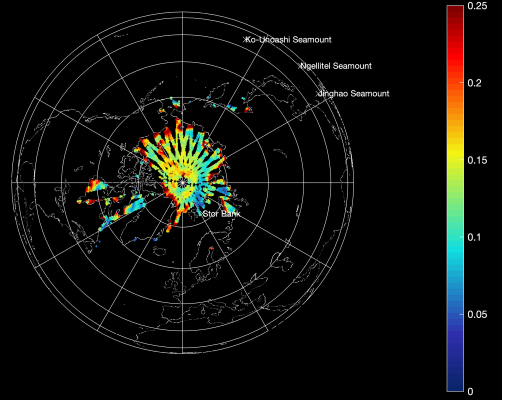
Sea ice thickness (m)

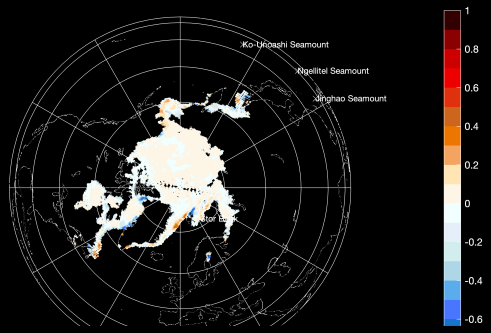


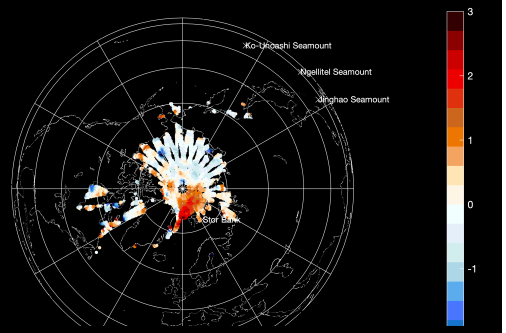
printing observation statistics:

region	obs.type	# obs.	|for.inn.|	|an.inn.|	for.inn.	an.inn.	for.spread	an.spread
	SIC	119506	0.032	0.017	-0.009	-0.005	0.029	0.019
	-6	17072	0.030	0.016	-0.007	-0.002	0.029	0.019
	-5	17072	0.030	0.016	-0.008	-0.004	0.029	0.019
	-4	17073	0.031	0.015	-0.009	-0.005	0.029	0.019
	-3	17073	0.031	0.015	-0.009	-0.005	0.029	0.019
	-2	17072	0.034	0.018	-0.010	-0.006	0.029	0.019
	-1	17072	0.036	0.020	-0.011	-0.007	0.029	0.019
	0	17072	0.035	0.021	-0.010	-0.005	0.029	0.019
	OSISAF	119506	0.032	0.017	-0.009	-0.005	0.029	0.019
	SIT	61661	0.133	0.114	-0.123	-0.104	0.022	0.015
	-6	8796	0.116	0.102	-0.106	-0.092	0.016	0.011
	-5	8786	0.121	0.104	-0.112	-0.095	0.017	0.012
	-4	8772	0.119	0.101	-0.110	-0.092	0.019	0.013
	-3	8798	0.133	0.114	-0.123	-0.104	0.021	0.014
	-2	8828	0.142	0.121	-0.132	-0.112	0.024	0.016
	-1	8831	0.145	0.123	-0.135	-0.114	0.026	0.017
	0	8850	0.152	0.131	-0.142	-0.122	0.029	0.019
	OSISAF	61661	0.133	0.114	-0.123	-0.104	0.022	0.015
	SIH	3430	0.566	0.527	0.086	0.101	0.146	0.099
	c2	3430	0.566	0.527	0.086	0.101	0.146	0.099
	SIH2	3358	0.628	0.634	0.186	0.197	0.160	0.111
	NASA	3358	0.628	0.634	0.186	0.197	0.160	0.111









- CAFE does multicategory ice concentration and thickness assimilation
- SMOS L4 has weekly Cryosat2 thick ice merged with SMOS thin ice from 2010-2020

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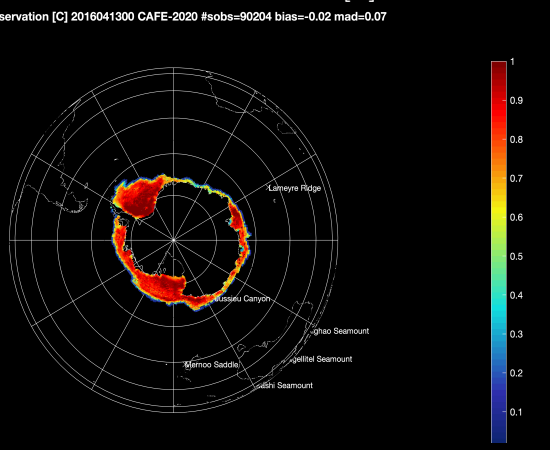
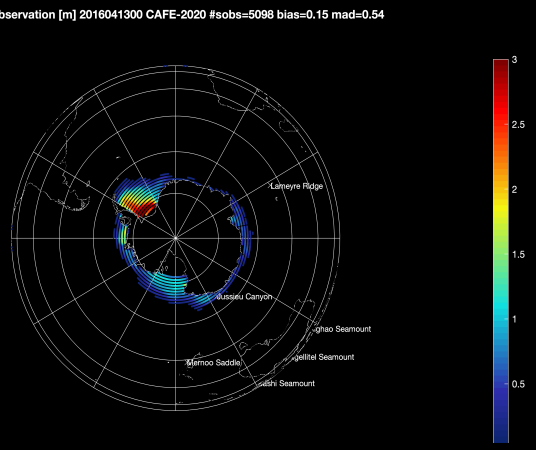
Coupled data assimilation in the CSIRO CAFE system

Assimilation of OSISAF and NASA GIOMAS sea-ice area and thickness data for Antarctic

Sea-ice concentration [C]



Sea ice thickness (m)

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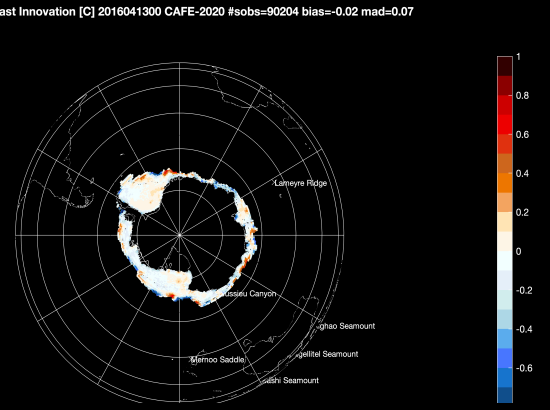
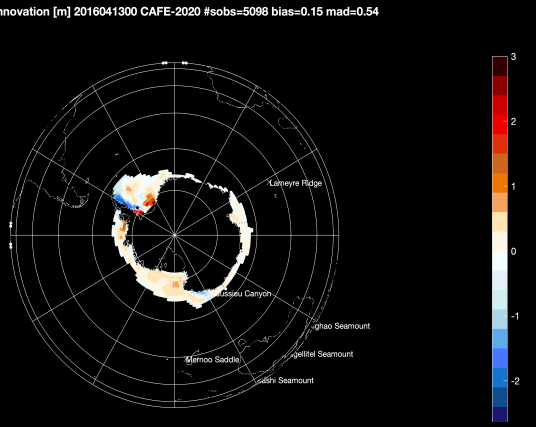
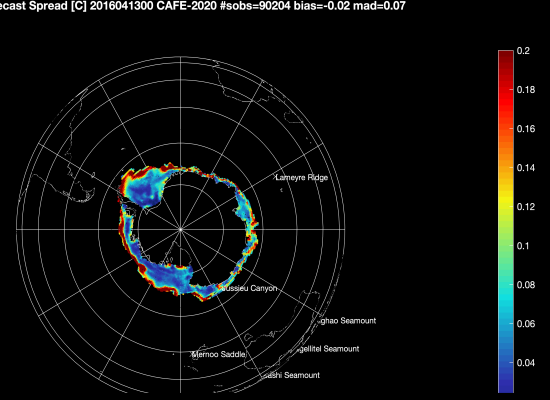
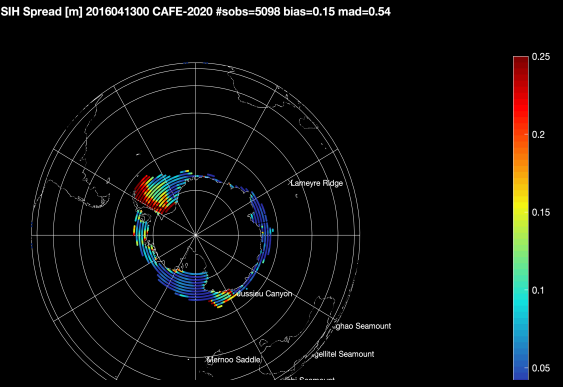
printing observation statistics:
  region obs.type   # obs.  |for.inn.| |an.inn.|   for.inn.   an.inn.  for.spread  an.spread
  ------------------------------------------------------------------------------------------
       SIC        132041    0.035      0.016      -0.017      -0.006      0.023       0.015
        -6         18863    0.036      0.019      -0.026      -0.015      0.023       0.015
        -5         18863    0.035      0.017      -0.022      -0.011      0.023       0.015
        -4         18863    0.035      0.016      -0.018      -0.007      0.023       0.015
        -3         18863    0.034      0.015      -0.016      -0.005      0.023       0.015
        -2         18863    0.035      0.016      -0.017      -0.006      0.023       0.015
        -1         18863    0.034      0.016      -0.012      -0.001      0.023       0.015
         0         18863    0.033      0.016      -0.009       0.002      0.023       0.015
    OSISAF        132041    0.035      0.016      -0.017      -0.006      0.023       0.015
       SIT         31067    0.061      0.044      -0.031      -0.019      0.023       0.016
        -6          4305    0.060      0.045      -0.033      -0.018      0.021       0.014
        -5          4361    0.059      0.043      -0.032      -0.018      0.021       0.014
        -4          4392    0.057      0.040      -0.029      -0.016      0.022       0.015
        -3          4420    0.058      0.041      -0.028      -0.016      0.022       0.015
        -2          4466    0.061      0.042      -0.029      -0.018      0.024       0.016
        -1          4554    0.067      0.047      -0.035      -0.022      0.026       0.018
         0          4569    0.065      0.048      -0.033      -0.022      0.027       0.018
    OSISAF         31067    0.061      0.044      -0.031      -0.019      0.023       0.016
      SIH2          1748    0.365      0.361       0.083       0.088      0.099       0.069
      NASA          1748    0.365      0.361       0.083       0.088      0.099       0.069
```









- CAFE does multicategory ice concentration and thickness assimilation
- GIOMAS is monthly mean analysis rather than observation and is about all there is for Antarctica

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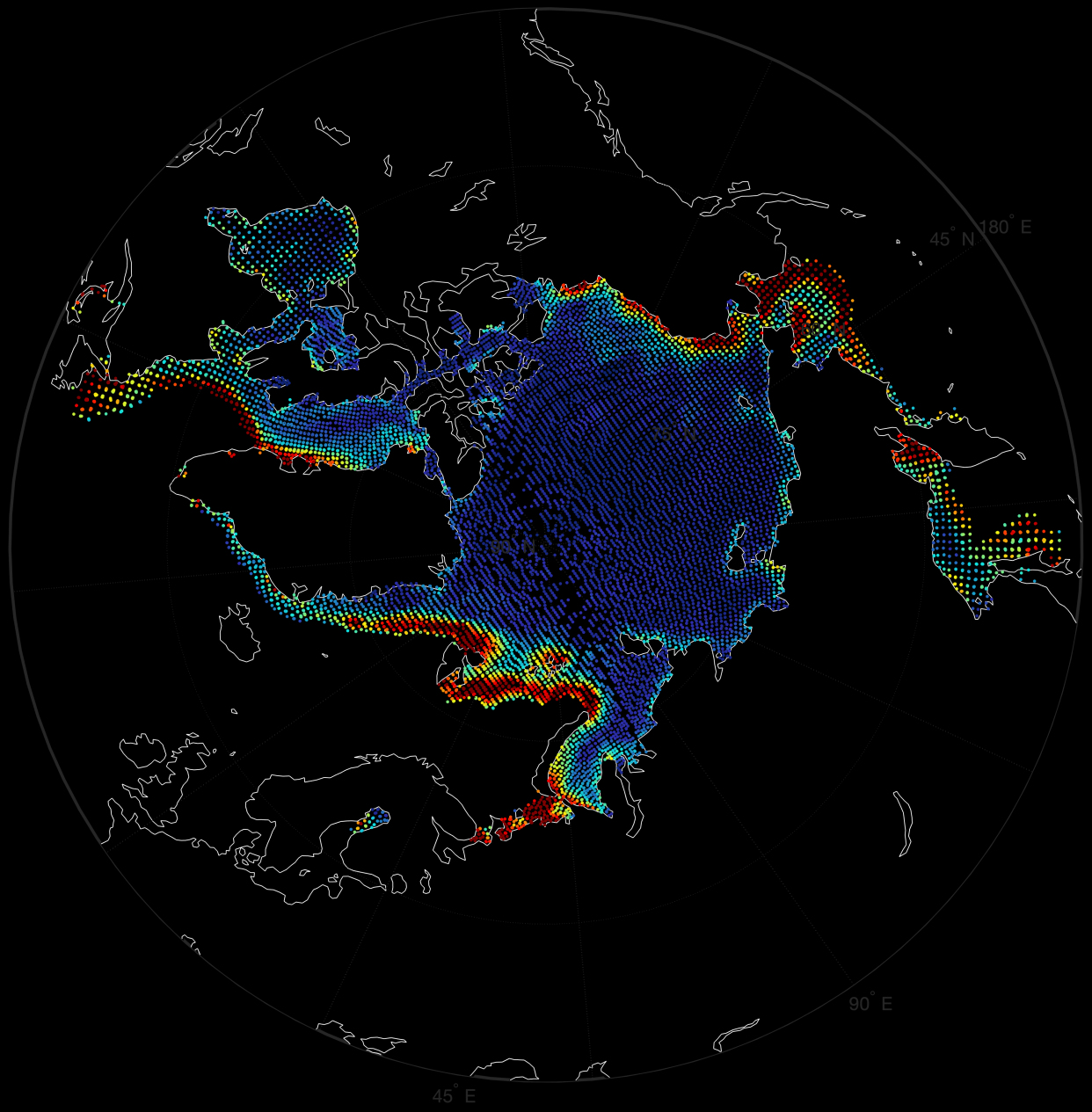
Coupled data assimilation in the CSIRO CAFE system

Conclusions

- Model error and model representation of error (spread) remain a challenge, particularly for the deeper ocean, tropical atmosphere, stratosphere and sea-ice where low variability exists at the resolved scales
- Improvements have been made to reduce bias in the forecast model using EnKF parameter estimation (Kitsios, et al, 2020)
- Observation impact becomes larger in coupled DA via cross-covariances
- The CAFE system is also being used to explore ensembles using weak perturbed sea-ice and ocean mixing physics and the use of an additional stochastic energetic forcing term within the ocean model for unresolved sub-grid-scale energy.
- Hybrid static-dynamic covariances using EnKF-C (Sakov, 2020)
- Planned update to GFDL CM4 (MOM6/AM4/SIS2/LM4)



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