Classification of Global Ocean SAR Images for Broader Applications

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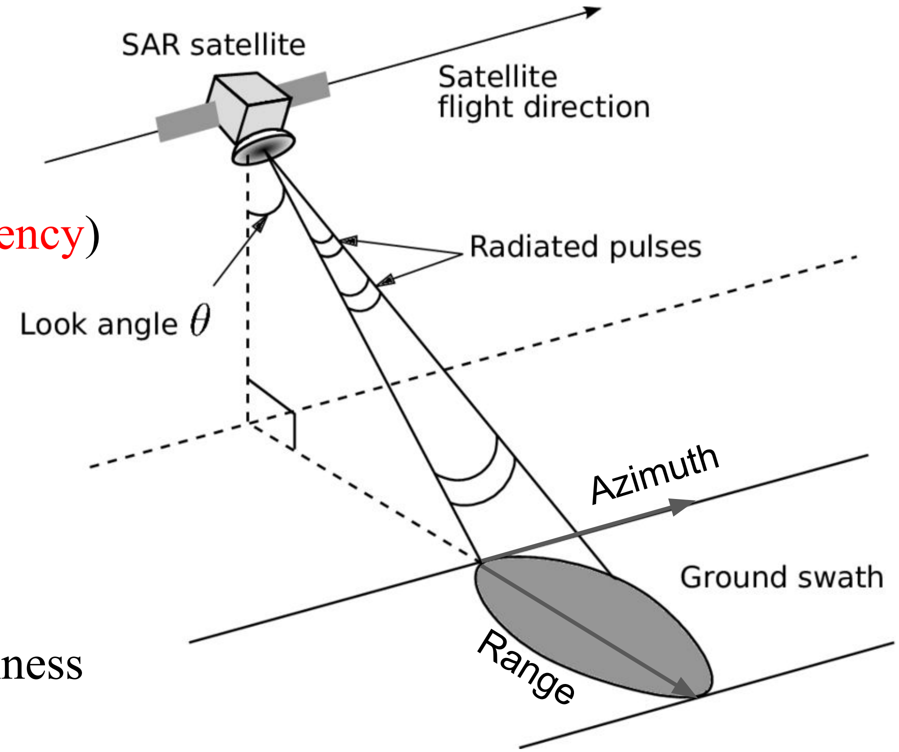
Background: SAR Basics

Synthetic Aperture Radar (SAR):

- Passive remote sensing
    - Nearly all weather capability
    - Day-and-night capability
    - Measure 2-D images
- Side-looking, usually right
    - 20°-50° incidence angle
    - Range resolution: R_r=c/2B (radar frequency)
    - Azimuth resolution: R_a=L/2 (synthetic)
- 2-D images of Earth surface
    - High-resolution: meter-scale
    - Wide coverage: 20-400 km
    - Sensitive to **cm-scale** sea surface roughness

Band	*Frequency (GHz)*	*Wavelength (cm)*
P	0.255 - 0.390	133 - 76.9
L	0.390 - 1.550	76.9 - 19.3
S	1.550 - 4.20	19.3 - 7.1
C	4.20 - 5.75	7.1 - 5.2
X	5.75 - 10.90	5.2 - 2.7



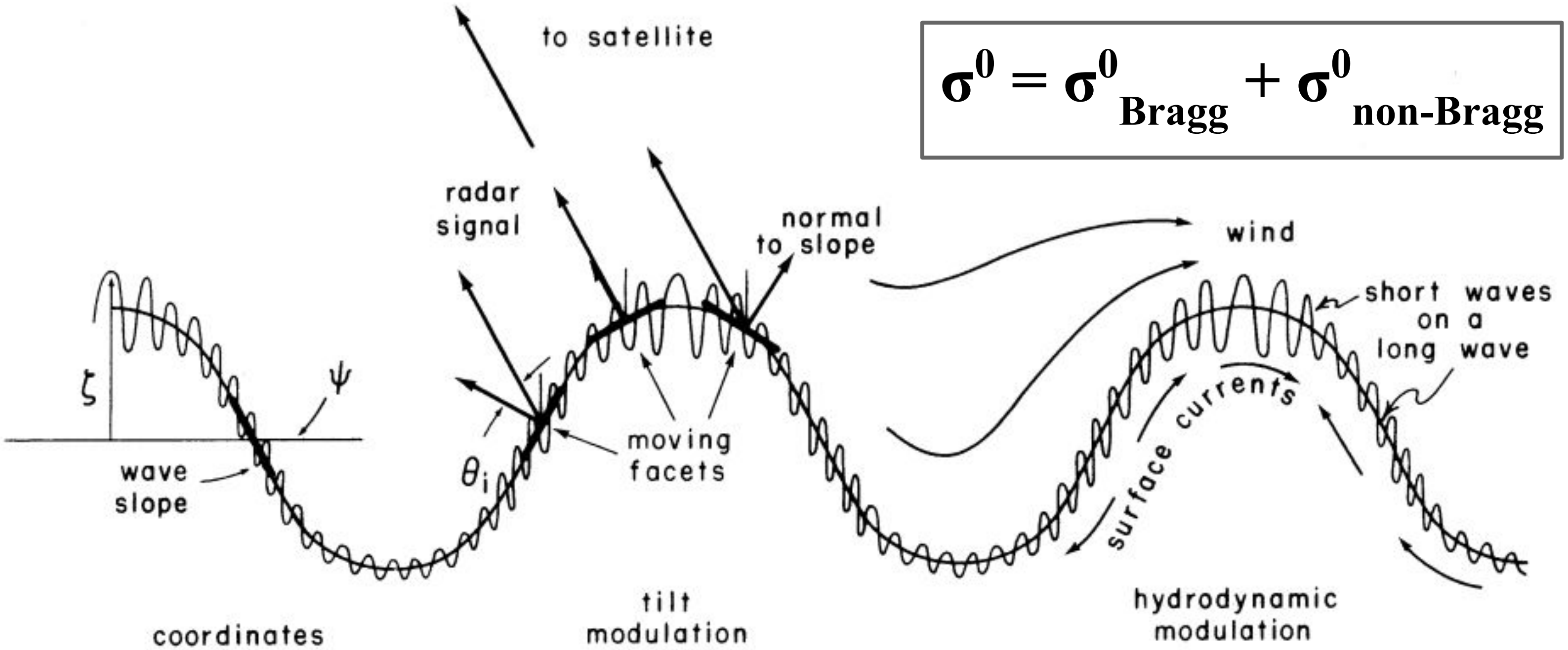
Jackson, C. R., Apel, J. R. and Editors (2004) *Synthetic Aperture Radar Marine User's Manual*.

Background: SAR imaging of ocean surface

Long waves

- Modulate **short waves**
  - More, mostly directional to along-wind
- Generate **wave breaking**
  - Less, but isotropic

$$\sigma^0 = \sigma^0_{\text{Bragg}} + \sigma^0_{\text{non-Bragg}}$$



Background: Ocean SAR & Applications

Satellite	Year	Band & wavelength (cm)
SEASAT	1978	L-band (23.5)
ERS-1/2	1991-2003	C-band (5.7)
Radarsat-1	1995-2012	C-band (5.7)
Envisat	2002-2012	C-band (5.7)
ALOS-1	2008-2011	L-band (23.5)
Cosmo-SkyMed	2007-	X-band (3.1)
TerraSAR-X	2007-	X-band (3.1)
Radarsat-2	2007-	C-band (5.7)
TanDEM-X	2010-	X-band (3.1)
ALOS-2	2014-	L-band (23.5)
Sentinel-1	2014-	C-band (5.7)
Gaofen-3	2016-	C-band (5.7)
Radarsat Constellation	2019-	C-band (5.7)

Ocean surface processes

- Surface waves: *O*(100-600 m)
- Internal waves: *O*(0.3-5 km)
- Internal tides: *O*(10-20 km)
- Currents : *O*(1-100 km)
- Oceanic fronts: *O*(1-400 km)
- Eddies: *O*(1-200 km)
- Bathymetry: *O*(5-50 m)

Atmospheric boundary layer processes

- Surface winds: *O*(<1 km)
- Roll vortices: *O*(0.6-10 km)
- Convective cells: *O*(0.6-10 km)
- Gravity waves: *O*(1-10 km)
- Rain cells: *O*(0.3-200 km)
- Atmospheric fonts: *O*(1-400 km)

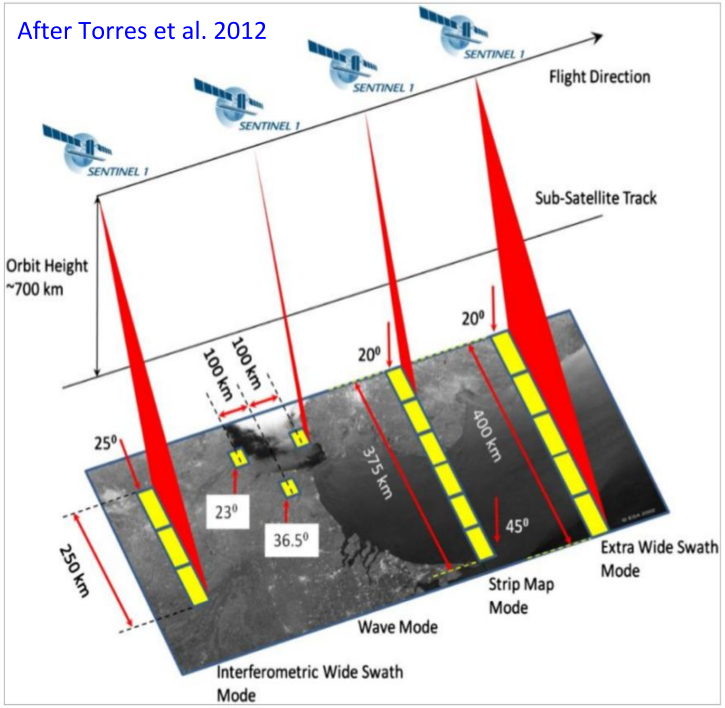
Others

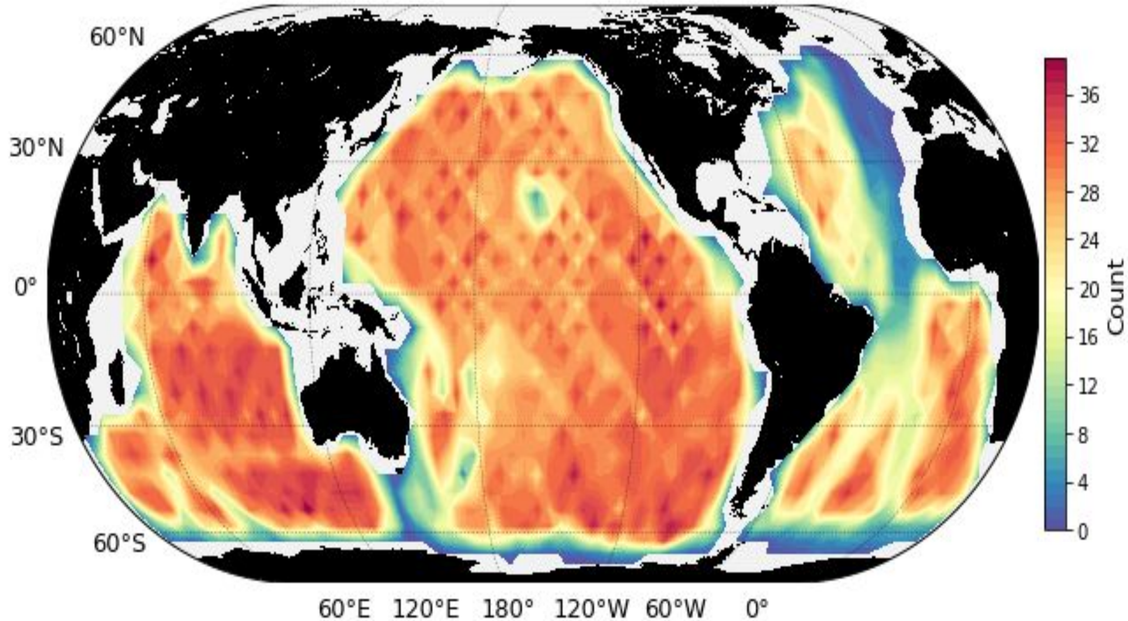
- Biogenic slicks: *O*(<100 km^2)
- Mineral oils: *O*(<100 km^2)
- Icebergs: *O*(< 1 km)
- Sea ice

……

Brand-new: Sentinel-1 wave mode

After Torres et al. 2012





Spatial gridded monthly average of Sentinel-1A WV2 acquisitions in 2016 and 2017. The color denotes number of SAR images in each 5° by 5° grid box

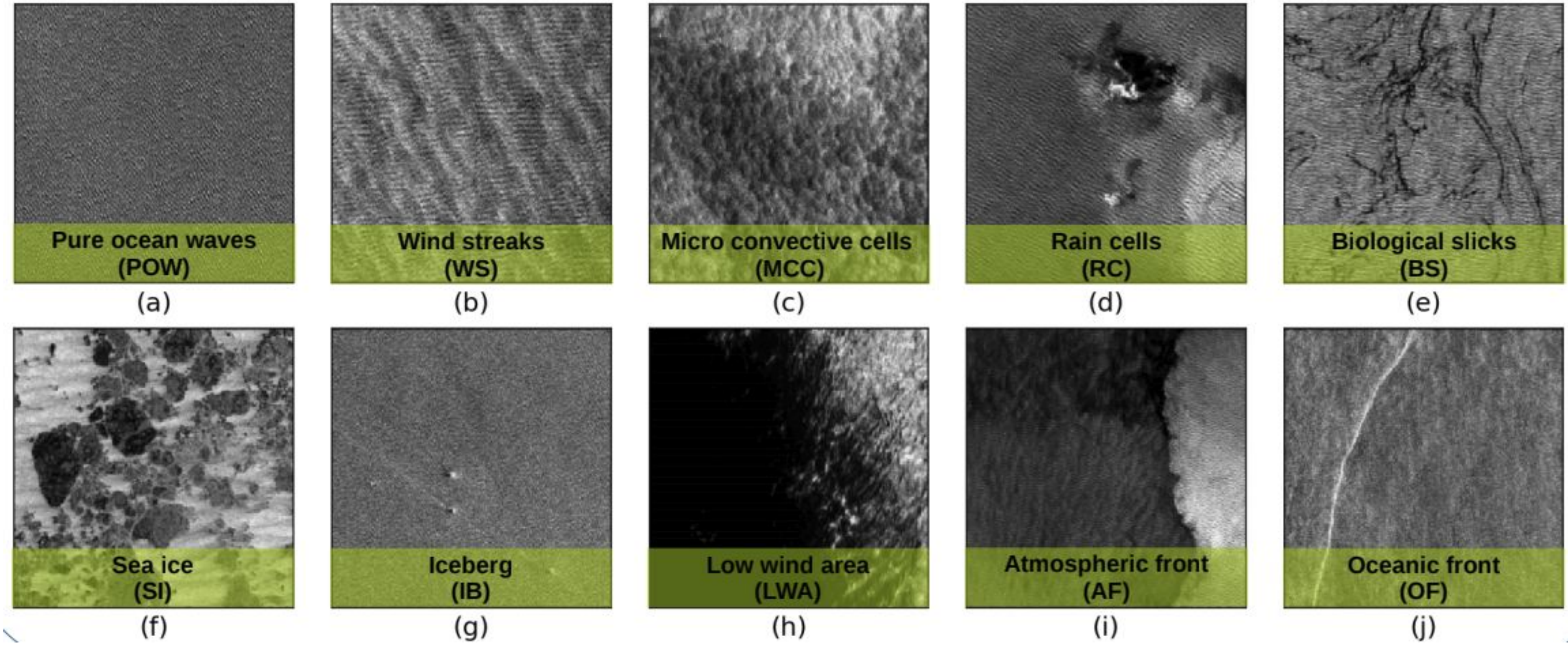
Sentinel-1 (S-1) wave mode (WV)

- C-band SAR satellite constellation
  - S-1 A starting in 2016, S-1 B in 2017
  - S-1 C&D in the near further
- Global wave mode acquisition
  - Default operating over open ocean
  - 20 × 20 km, 5 m resolution SAR images
  - Two incidence angles: 23° (WV1), 36.5° (WV2)
- ~30,000 images/month/satellite/mode
  - Nearly global and systematic
  - Gaps in time and space

➢ Coverage very good in Pacific, Indian Ocean, and Southern Oceans

➢ Captures many different types of ocean surface processes

Brand-new: km-scale processes



- ➢ These ocean surface processes are obviously distinguishable
- ➢ Could we properly define these geophysical phenomena?
- ➢ How to automatically classify these geophysical phenomena?
  - A challenge for traditional methods that use hand-created parameters
  - Machine/Deep-learning is the future

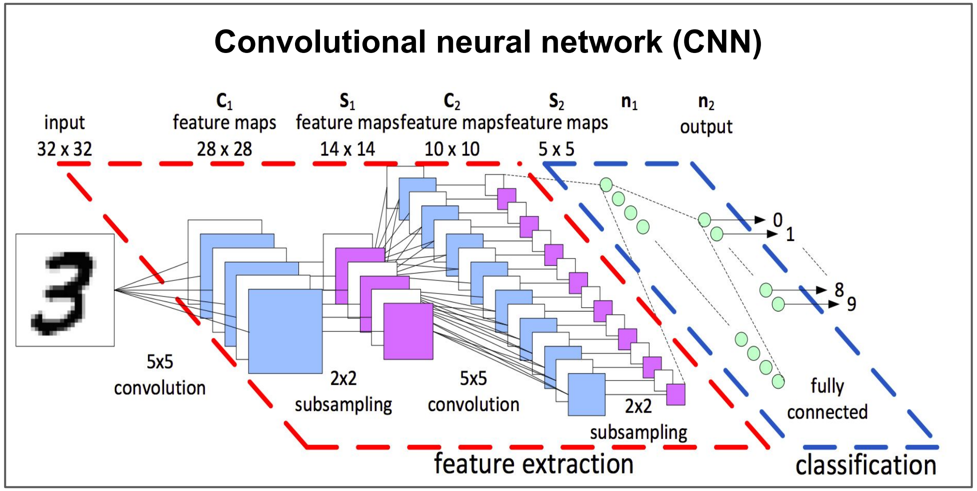
Labelled dataset: TenGeoP-SARwv

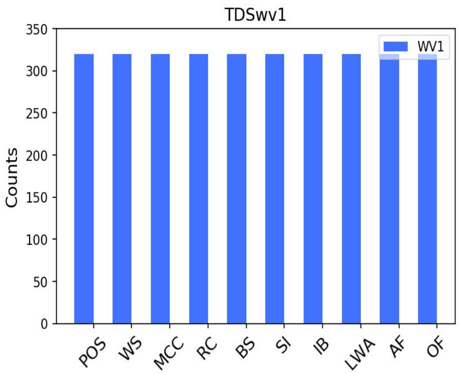
TABLE 1 SAR image numbers of the labelled dataset for each class in every month of 2016

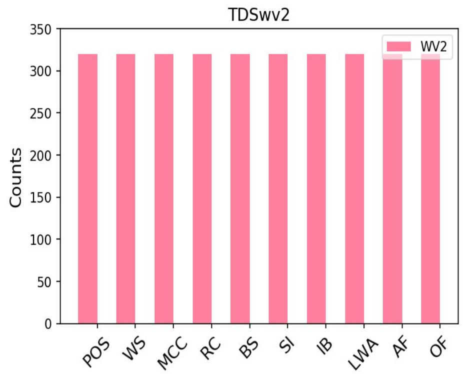
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
POW	406	407	408	409	406	408	410	409	409	409	408	411	4,900
WS	406	409	403	407	404	391	396	398	397	398	384	404	4,797
MCC	396	384	370	384	385	365	386	388	380	391	384	385	4,598
RC	398	399	398	395	398	391	395	393	393	396	394	390	4,740
BS	398	394	395	398	397	339	397	398	397	400	398	398	4,709
SI	387	150	282	396	396	392	393	393	396	396	396	393	4,370
IB	399	417	308	146	58	29	10	14	12	29	159	399	1,980
LWA	137	137	138	220	201	95	214	144	207	207	241	219	2,160
AF	360	282	301	348	363	234	361	377	378	367	364	365	4,100
OF	61	85	64	102	131	60	116	135	96	108	132	109	1,199
Total	3,348	3,064	3,067	3,205	3,139	2,704	3,078	3,049	3,065	3,101	3,260	3,473	37,553

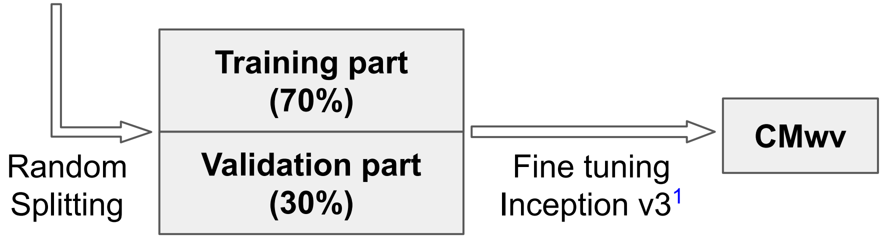
- ➢ 10 commonly observed phenomena from Sentinel-1 wave mode (Wang et al., 2019, GDJ)
- ➢ Handy-selected dataset: **TenGeoP-SARwv** (https://doi.org/10.17882/56796)
  - 10 geophysical classes
  - >1000 images/class
  - Single-labelling
  - Almost monthly-balanced

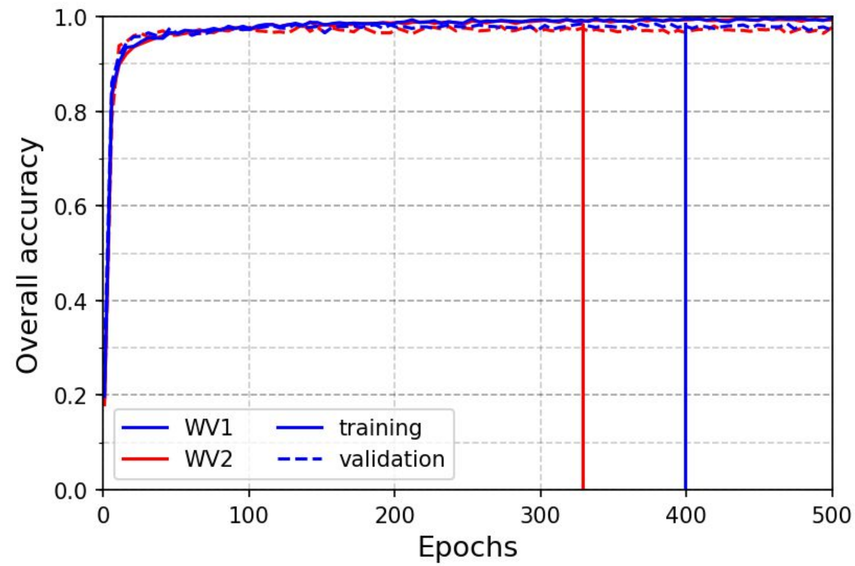
Deep-CNN classifier: CMwv model









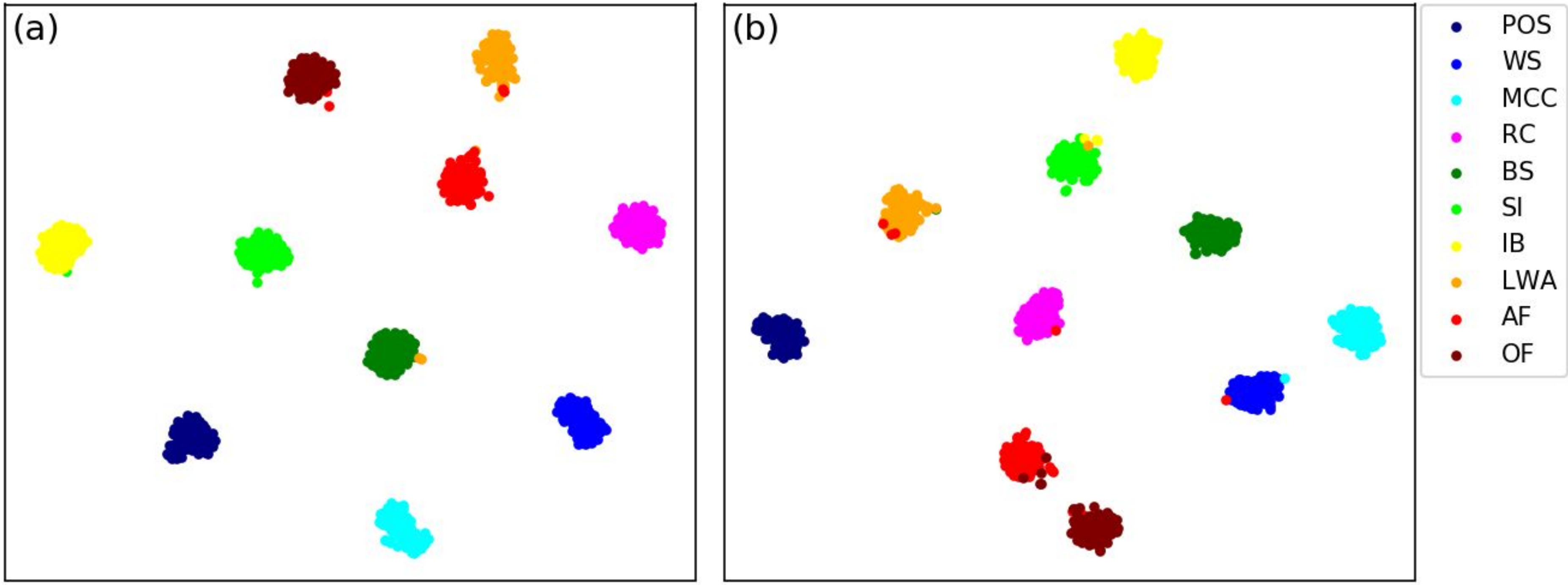


Overall accuracy of training (solid lines) and validation (dashed lines) shown in each 5 epoch for WV1 (blue lines) and WV2 (red lines), respectively.

- Overall accuracy on validation part reaches 0.98 for both WV1 and WV2.
- Effectiveness of fine tuning Inception v3 based on small training dataset.

[1] Szegedy et al., 2015, Rethinking the Inception Architecture for Computer Vision.

Deep-CNN classifier: extracted features



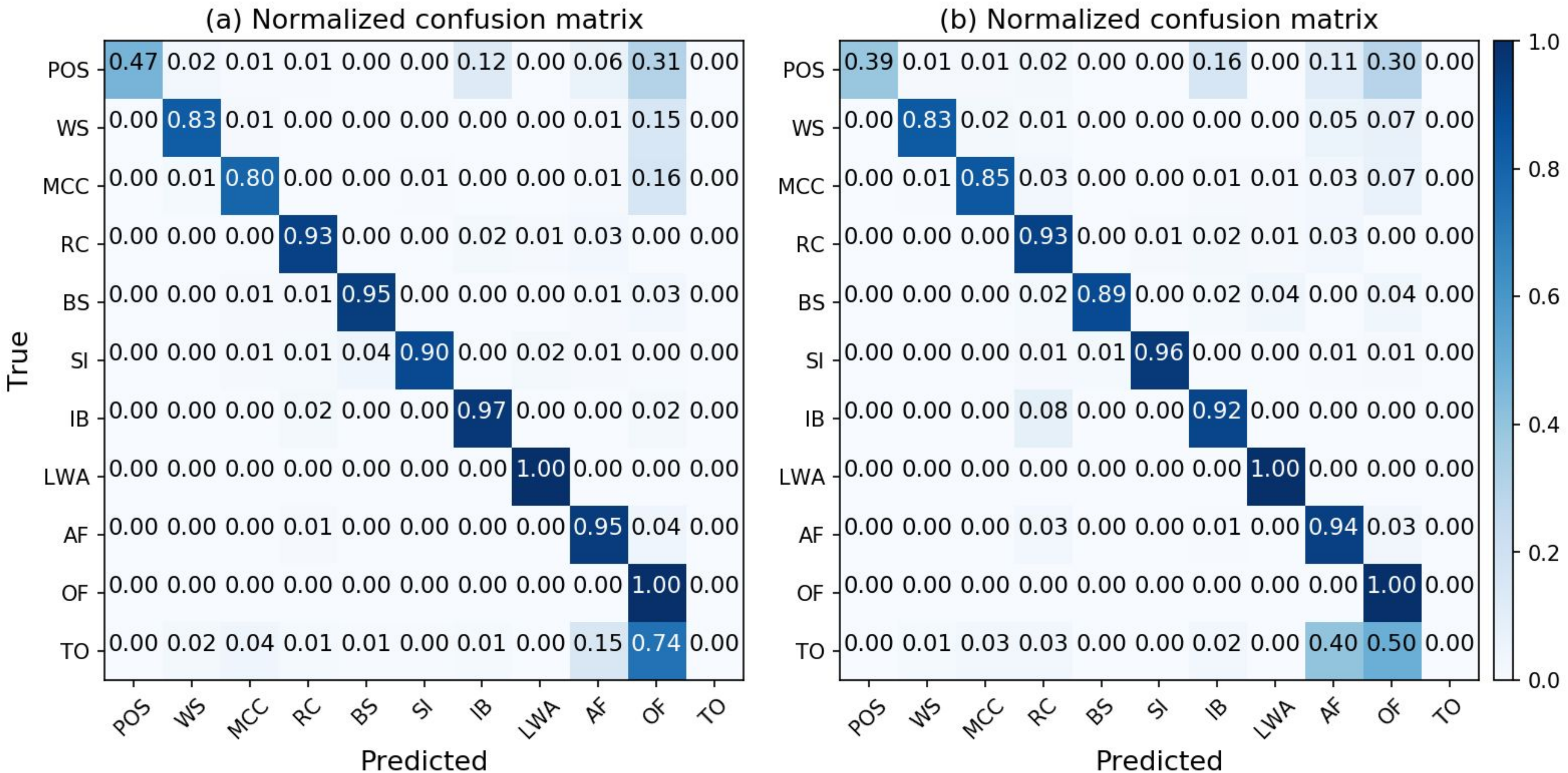
Two-dimensional scatter plots of the extracted 2048 image features decomposed by t-SNE[1] over the validation part vignettes for (a) WV1 and (b) WV2. The 10 geophysical classes are marked with different colors.

- Each class of the ten is well clustered and distinct from the others
- Extracted image features by CMwv should effective to distinguish the SAR images
- Distances between two clusters are not measures of the model performance

[1] Maaten, et al., 2008, Visualizing Data using t-SNE

Deep-CNN classifier: model performance

- ➢ Assessment dataset: 5000 vignettes of WV1 and WV2, respectively
- ➢ Evaluate the classification results by visual inspection.
- ➢ Special category of the others (TO).



Normalized confusion matrix of classification results over the assessment dataset for (a) WV1 and (b) WV2.

Deep-CNN classifier: model performance

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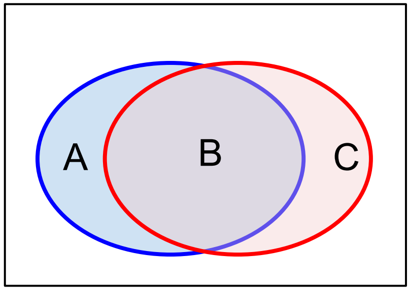
$$recall : \frac{\textit{number of correctly predicted}}{\textit{number of truth}}$$

$$precision : \frac{\textit{number of correctly predicted}}{\textit{number of predicted}}$$

$$Fscore : \frac{2*precision*recall}{precision+recall}$$



Correctly predicted: B
Truth: A+B
Predicted: B+C

Recall: B/(A+B)
Precision: B/(B+C)
Fscore: (2***R*****P**)/(**R**+**P**)

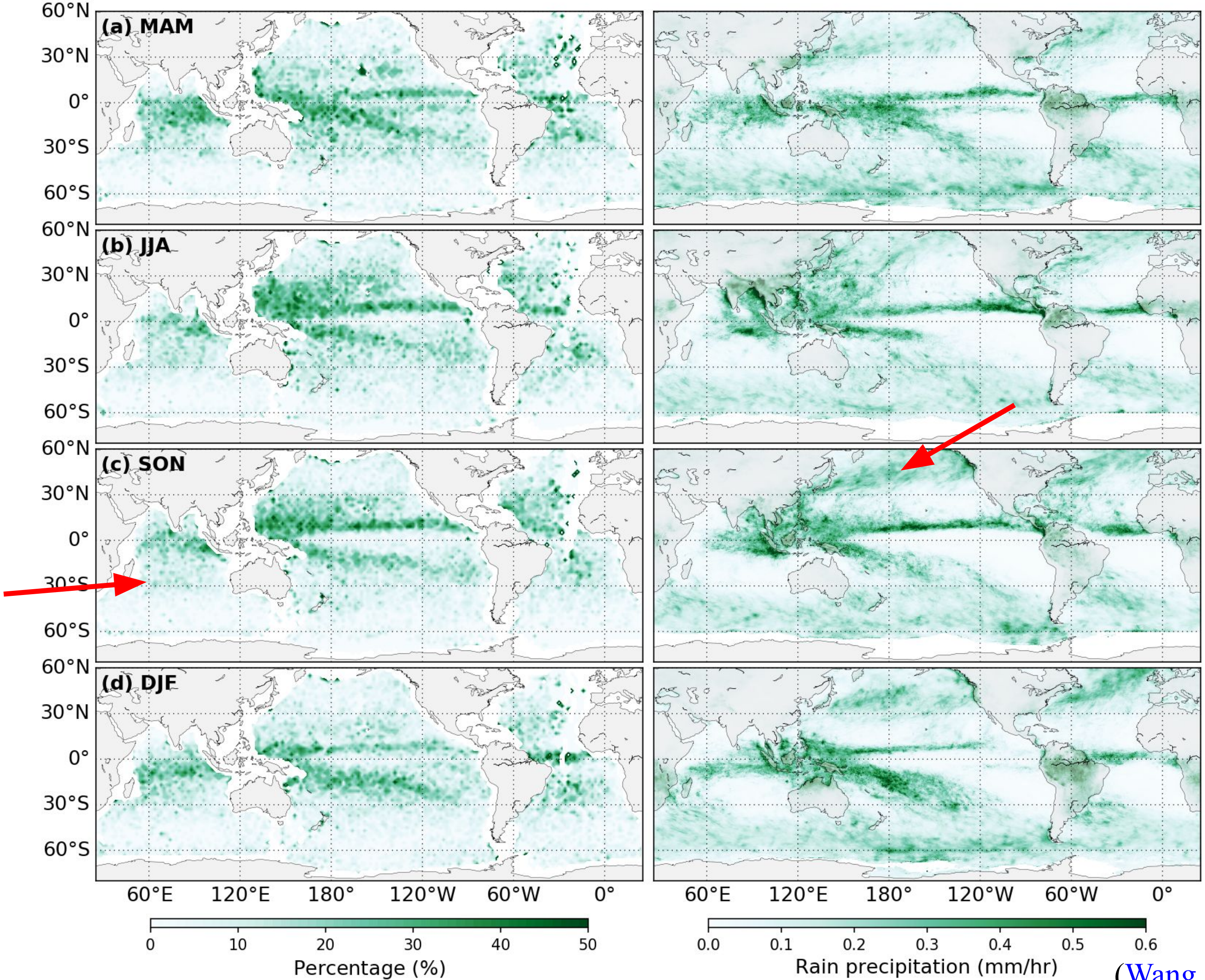
Table 1: CMwv recall, precision and F-score metrics for each of the 10 geophysical categories when applied to WV1 (upper) and WV2 (lower) vignette detection.

	POW	WS	MCC	RC	BS	SI	IB	LWA	AF	OF
Recall	0.47	0.83	0.80	0.93	0.95	0.90	0.97	1.00	0.95	1.00
	0.39	0.83	0.85	0.93	0.89	0.96	0.92	1.00	0.94	1.00
Precision	1.00	0.77	0.76	0.88	0.88	0.96	0.16	0.87	0.39	0.02
	0.98	0.96	0.94	0.80	0.91	0.96	0.18	0.79	0.38	0.02
F-score	0.64	0.80	0.78	0.90	0.91	0.93	0.27	0.93	0.56	0.04
	0.56	0.89	0.89	0.86	0.90	0.96	0.30	0.88	0.54	0.04

- WS, MCC, RC, BS, SI and LWA have high Fscore for both WV1 and WV2.
- Other classes need to be improved in the future classification models

Geophysical validation: Rain events

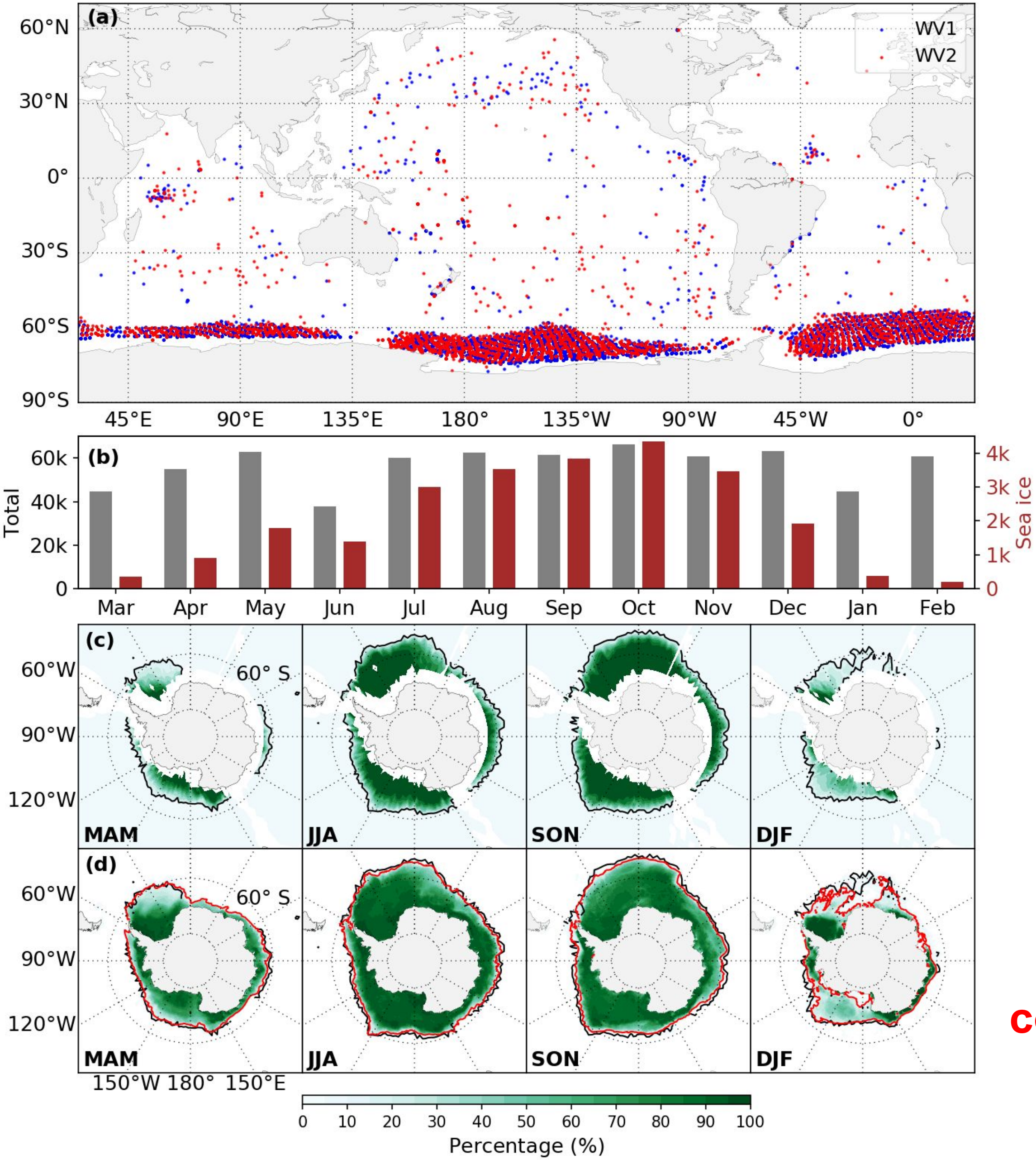
Classified RC (Left) v.s. GPM rain precipitation (Right)



(Wang et al., 2019, RSE)

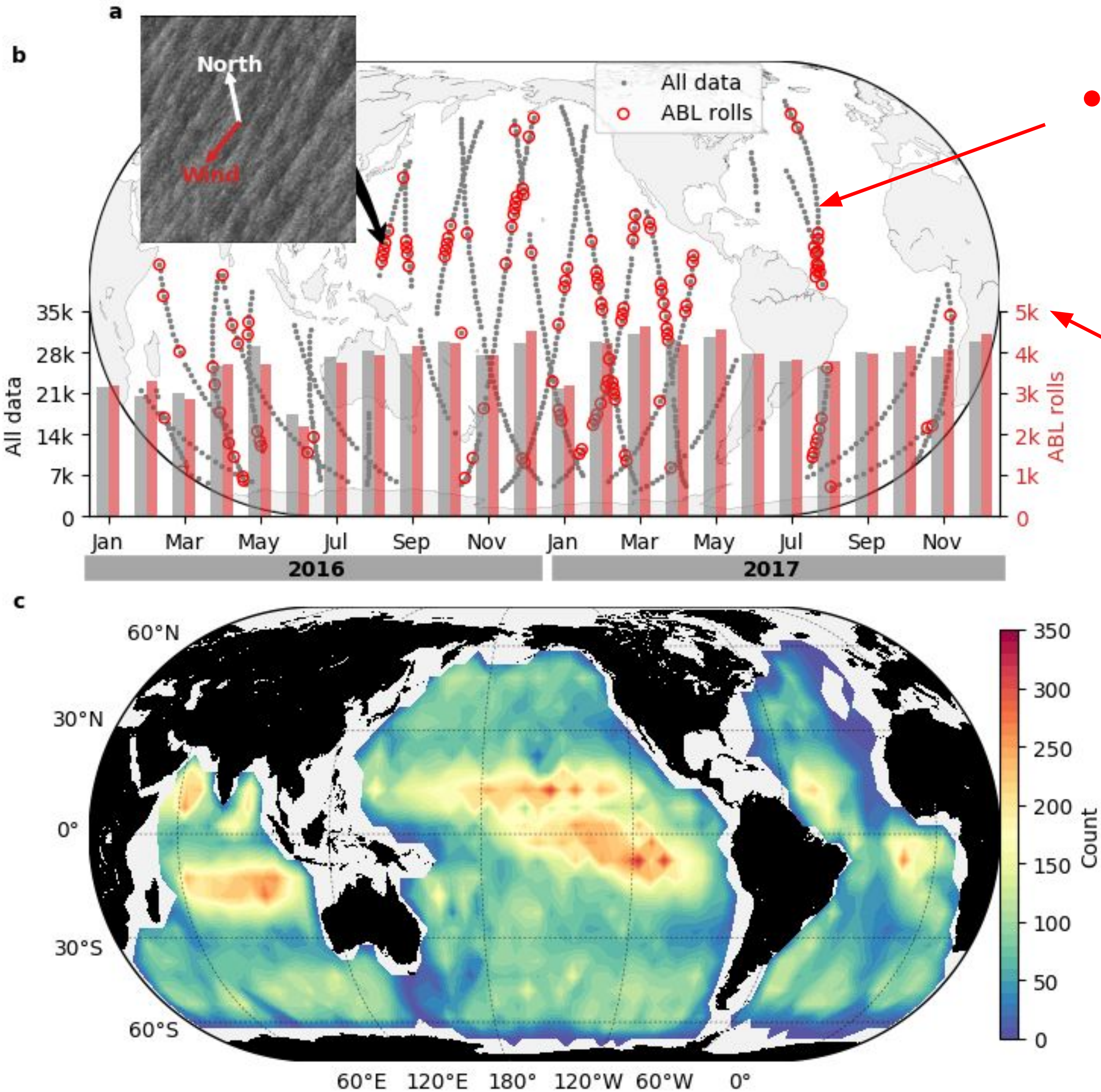
Geophysical validation: Sea ice

Classified SI (a-c)



SSMI SI concentration (d)

Broader application: MABL rolls

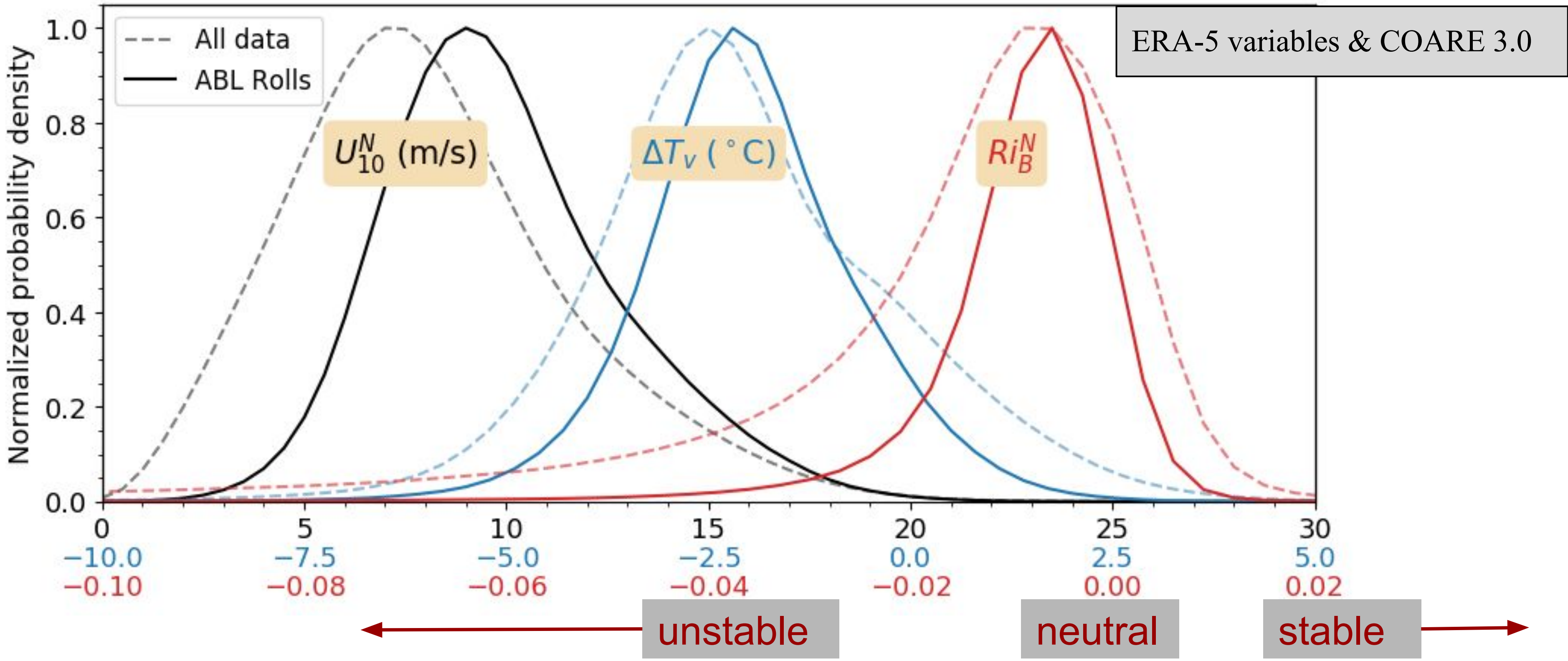


- 1 Day of detected MABL roll events

- ~4k/month
- Lower limit, ~15% rolls

- Roll vortices present across the whole ocean as expected
- More prevalent in the tropics, located alongside rainfall belts

Broader application: MABL rolls

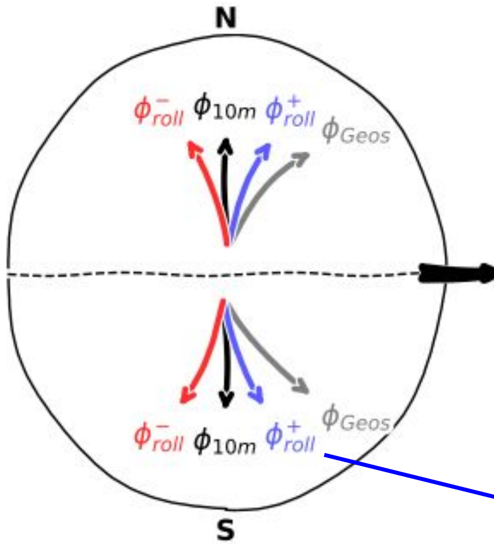


- Atmospheric conditions of detected rolls are **distinct** from the overall average conditions
- **Stronger surface wind**: 5-17 m/s, centred at 9 m/s
- **Less unstable Air-Surface temperature difference**: -4.5-0.5 °C, centred at -2 °C
- **Slightly unstable to near-neutral** (**expected**): -0.02-0.005, centred at -0.0075

Broader application: MABL rolls

$$AR = \lambda / h$$

Where λ is roll wavelength, and h is the boundary layer height.



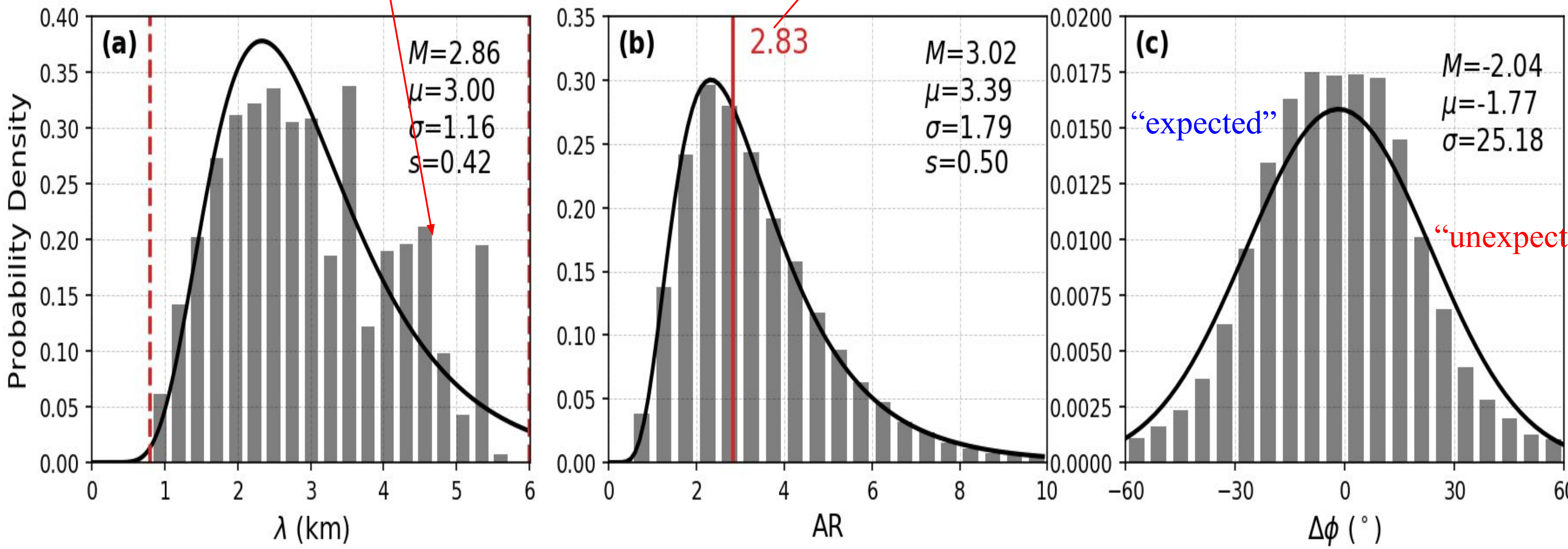
$$\Delta\phi = (\phi_{10m} - \phi_{rolls}) \cdot \mathrm{sign}(lat)$$

Positive indicates that rolls orientation is on the right/left of surface winds in the northern/southern hemisphere.

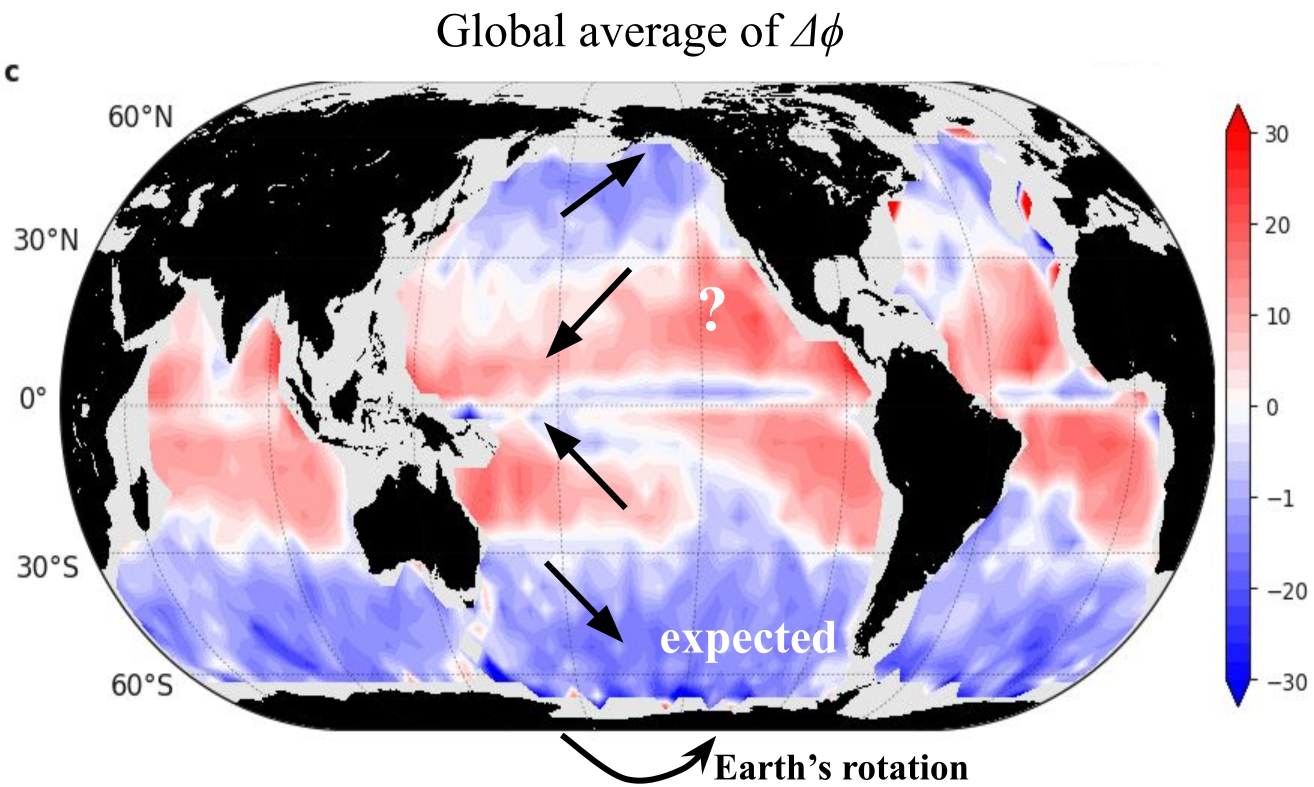
"Expected" based on most of roll theories.

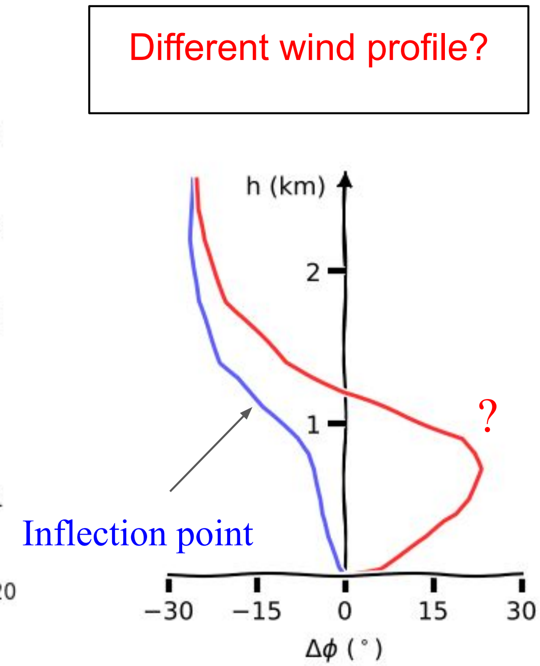
Discrete due to the poor FFT spectrum resolution

Theory prediction



Broader application: MABL rolls

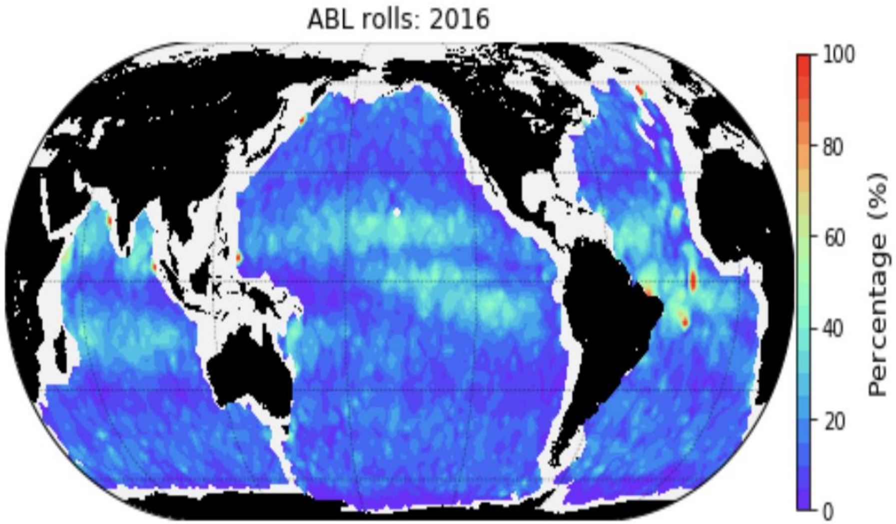


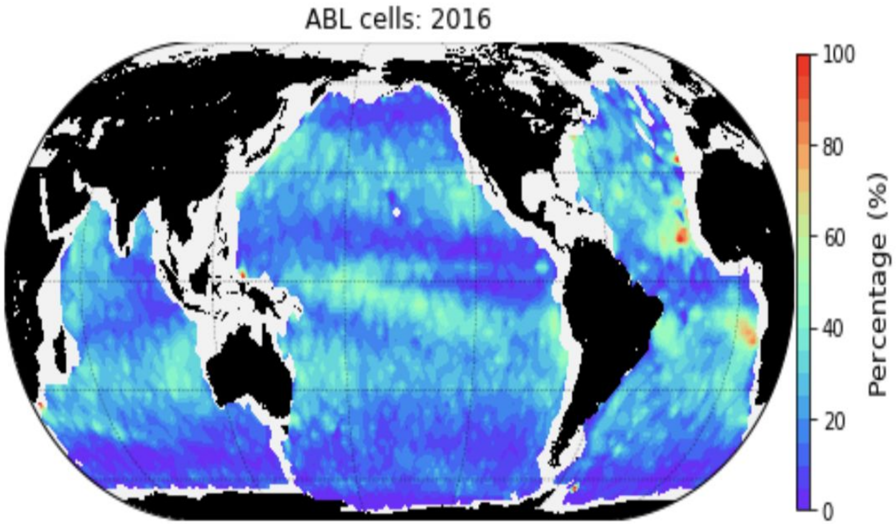


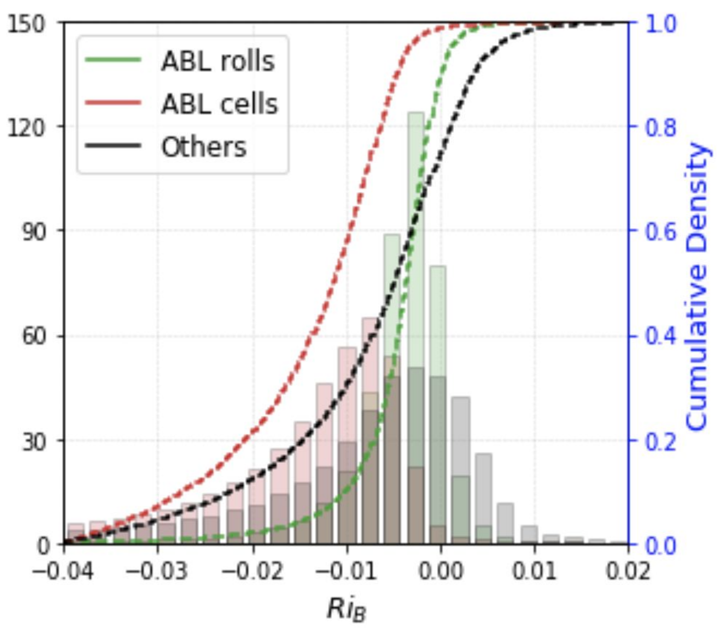
Most Puzzling – what's a few degrees in wind direction amongst friends?

- Orientation of the OLE direction with respect to surface is expected to be -15 deg.
- Lies between Surface and Geostrophic wind atop ABL
- **But – we see subtropical shift to OLE field that swings past surface wind direction????**

Broader application: MABL roll-cell transition

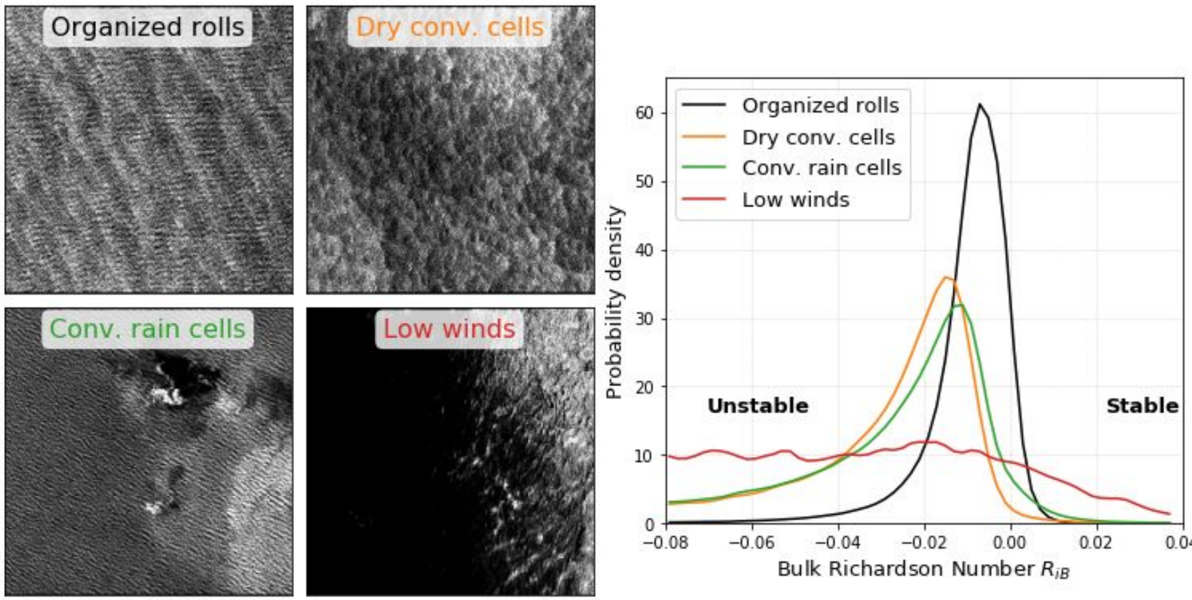


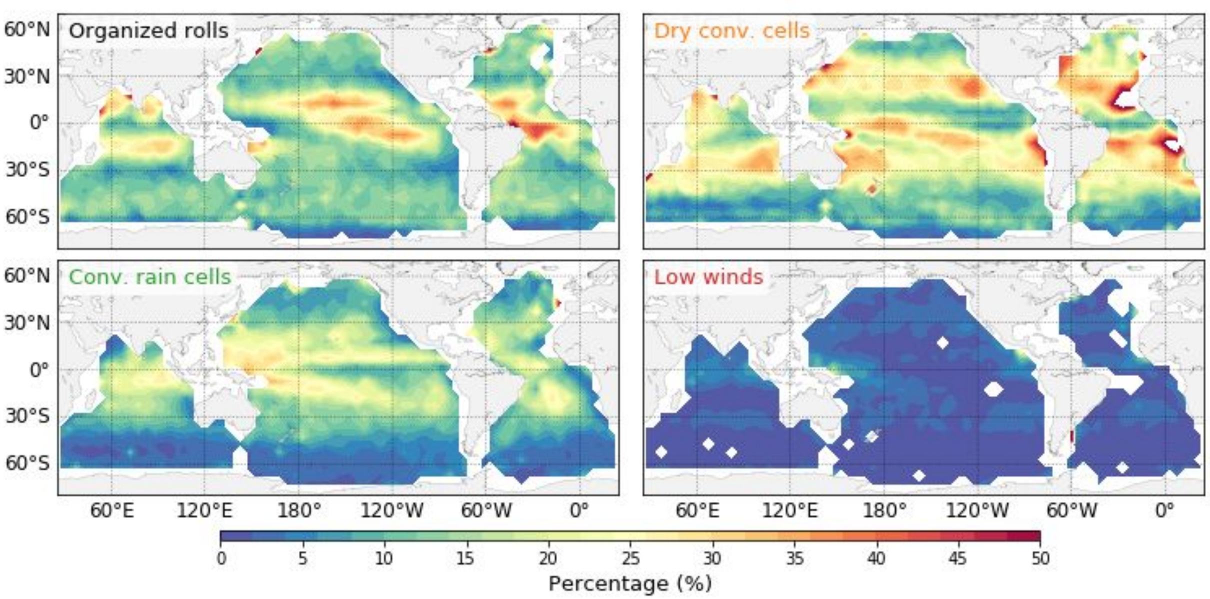




- Unstable for cells, near neutral for rolls
- Quite distinct separation
- Transitions between rolls and cells
- Should allow access to air-sea T

Broader application: MABL states





- Formation of these structures depends on the MABL state
- linkages between SAR observed MABL imprints and atmospheric stratifications
- Measure MABL overall state directly from SAR images?

Summary & New questions

S-1 SAR data gives new global view of ocean surface processes at 0.1-5 km scale

- Key geophysical ocean surface phenomena
    - Automatic classification benefits from **deep learning techniques**
- Biggest new results related to MABL rolls
    - Preliminary on prevalence (20-30% estimate), expected atmospheric conditions, roll wavelength and orientation.
    - Theoretical support in progress for the ‘unexpected’ roll orientation
- Separate studies on roll-cell transition, MABL state estimation, as well as many others...

Future directions (of many)

- From single-labelling to multi-labelling
- Include more geophysical categories (ocean surface processes)
- From wave mode SAR data to wide-swath SAR data
- Understand SAR imaging limitations
- Joint- analysis with other remote-sensed ocean data
- …...

Thanks for your attention !

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